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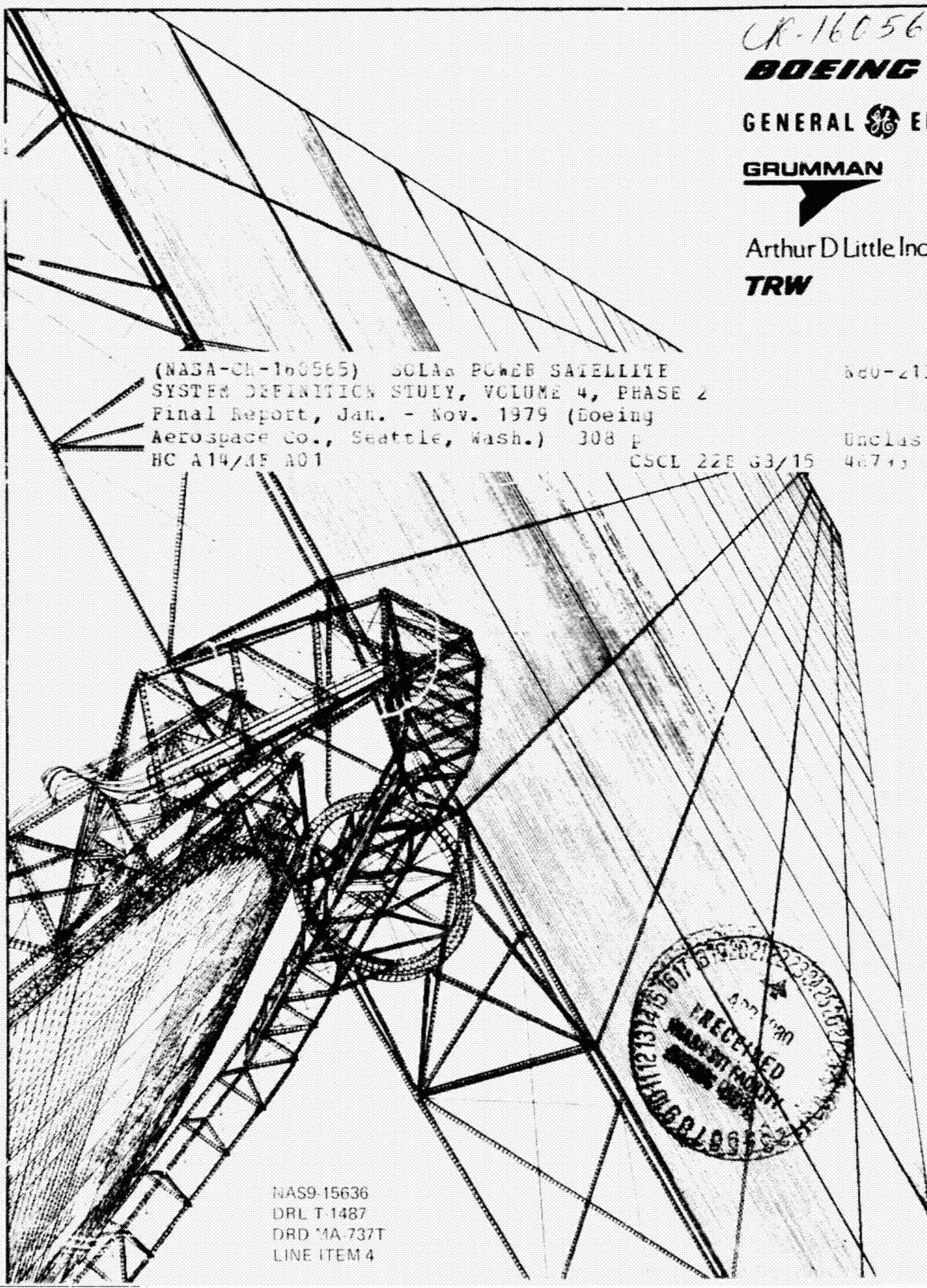
Solar Power Satellite System Definition Study

PHASE II
VOLUME IV
TECHNICAL ANALYSIS REPORT
D180-25461-4



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GENERAL ELECTRIC

GRUMMAN

Arthur D Little Inc

TRW

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SOLAR POWER SATELLITE
SYSTEM DEFINITION STUDY
Conducted for the NASA Johnson Space Center
Under Contract NAS9-15636

Volume IV
PHASE II, FINAL REPORT
Technical Analysis Document
D180-25461-4

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Approved By: G. R. Woodcock

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FOREWORD

The SPS System Definition Study was initiated in June of 1978. Phase I of this effort was completed in December of 1978 and was reported in seven volumes (Boeing document number D180-25037-1 through 7). Phase II of this study was started in January 1979 and was completed in November 1979. The Phase II study results are reported herewith. This study is a follow-on effort to an earlier study of the same title completed in March of 1978. These studies are a part of an overall SPS evaluation effort sponsored by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration.

This study is being managed by the Lyndon B. Johnson Space Center. The Contracting Officer is Thomas Mancusco. The Contracting Officer's representative and Study Technical Manager is Harold Benson. The study is being conducted by The Boeing Company with Arthur D. Little, General Electric, Grumman, TRW, and Brown and Root as subcontractors. The study manager for Boeing is Gordon Woodcock. Subcontractor managers are Dr. Philip Chapman (ADL), Roman Andryczyk (GE), Ronald McCaffrey (Grumman), Ronald Crisman (TRW), and Don Hervey (Brown and Root).

This report includes a total of five volumes:

- I - Executive Summary
- II - Reference System Description
- III - Operations and Systems Synthesis
- IV - Technical Analysis Report
- V - Phase II Final Briefing

Key team members that contributed in the various disciplines were the following:

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SOLAR POWER SATELLITE
SYSTEMS AND DEFINITION STUDY
PHASE II
TECHNICAL ANALYSIS REPORT

INTRODUCTION

This document is Volume IV of a 5-volume report on Phase II of the Solar Power Satellite Systems Definition Study, Contract NAS9-15636. The other volumes are:

- I - Executive Summary (covers Phase I and Phase II)
- II - Reference System Description and Cost Analysis
- III - Operations and Systems Synthesis
- V - Phase II Final Briefing

This volume serves to report those results of Phase II that do not logically fit into Volumes II or III. This document contains the following reports:

- Solid State SPS
- Parametric Development of Reliability Design for a Large Solar Power Satellite
- Solid State SPS Power Distribution
- Multibeam SPS
- GEO Construction Base Design and Analysis
- Suppressed Trajectories
- Offshore Space Center
- SPS Development and Operations Scenario
- MPTS Technology Advancement

SOLID-STATE SANDWICH CONFIGURATION

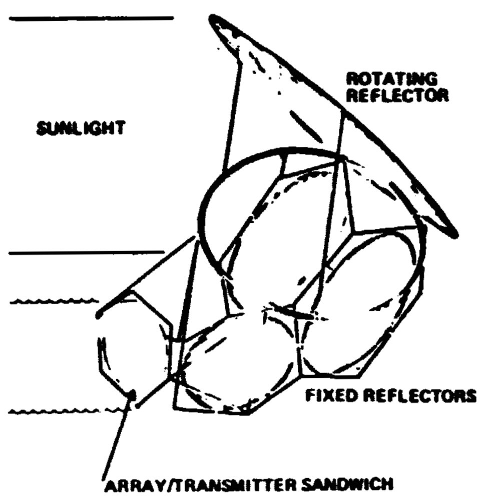
A new fundamentally different power satellite design, the "solid state sandwich" has been introduced by workers at MSFC. (See Figure 1) The basic idea behind the design is to put DC-microwave conversion elements and solar cells on opposite sides of the same surface, and use optical reflectors to satisfy illumination geometry requirements.

The greatest advantage of the sandwich design is that the close proximity of the generation of DC electrical power (by solar cells) and it's conversion to microwaves (by the DC-RF converters, assumed to be solid state) allows low voltages without excessive conductor loss. also, the electrical rotary joints are still necessary. In the event that effects of plasmas on high voltage surfaces on reference SPS designs turn out to be intractible, sandwich satellites may offer a way out.

The placing of solar cells and DC-RF convertors in the intimate proximity implicit in sandwich power satellite designs increases normal thermal constraints on RF power density. The reason for this is that the maximum microwave power output per unit area, $(P/A)_{RF}$ from a surface able to dissipate heat per unit area, (Q/A), is related to its power conversion efficiency, η, by the oft - seen equation:

$$(P/A)_{RF} = (1-\eta)^{-1} (\dot{Q}/A).$$

In a conventional power satellite (with separate transmitting antenna and solar array) η is the DC-RF conversion efficiency, which is expected to have typical values of around 8. On a sandwich power satellite, however, η is the product of the DC-RF conversion efficiency and the solar cell efficiency, given values of less than .2 with present cells. Thus, if the achievable (Q/A) is the same for both a sandwich and a conventional power satellite, the sandwich's peak $(P/A)_{RF}$ would be over a factor of 16 lower than the conventional design's. When this difference is integrated into a system design, large aperture, (circa 2 km diameter), lower power, (1 GW), designs result. These designs have a large relative fraction of transmitting array per unit RF power with a severe (x3) attendant cost penalty. The designer's basic goal is to reduce this with either low-cost aperture area (as being proposed by RCA) or system design and configuration "tricks" which use the aperture more effectively.



ADVANTAGES

- ELIMINATES POWER DISTRIBUTION & PROCESSING (AT LEAST MOST OF IT)
- ELIMINATES HIGH VOLTAGES
- ELIMINATES ELECTRICAL ROTARY JOINT
- MAY BE ADAPTABLE TO LARGE APERTURE, LOW POWER SYSTEMS

PROBLEMS

- THERMALLY-CONSTRAINED DESIGN
- HOW TO IMPLEMENT ILLUMINATION TAPER?
- MECHANICALLY & STRUCTURALLY COMPLICATED, HARD TO CONSTRUCT?

Figure 1. The Solar Cell Solid-State Sandwich SPS Concept

Figure 2 shows cost per unit installed grid power, delivered power and true concentration ratio as a function of temperature, as given by the initial parametric analysis. The satellite configuration for this analysis was a sandwich with uniform power taper and conventional GaAs or Si solar cells illuminated by a full solar spectrum.

Figure 2a shows that silicon cells are ruled out for sandwich use due to their efficiency degradation with temperature, resulting in costs over \$10,000/kw_e. Sandwich satellites with GaAs cells retain more performance but need to operate at high temperatures to match conventional satellite costs. Feasibility of such high temperature operations seems unlikely but needs further investigation.

If one sandwich layer can operate at higher temperatures than the other layer, insulating properly may minimize thermal output while maintaining design temperatures. While insulation may be the correct thing to do to maximize performance of a sandwich satellite design, the possible performance gains are limited for the following 3 reasons.

1) Solar cells are typically made of the same semiconductor materials as solid state DC - microwave devices and thus should suffer from roughly the same fundamental failure mechanisms. For GaAs lifetime goes down roughly a factor of 10 every 25°C. However, at 125°C it takes 75°C to double the radiated thermal power per unit area.
2) Placing solar cells and DC - microwave devices on opposite sides of the same plane cuts the available thermal radiating surface in half relative to separate arrays.
3) Insulation inevitably adds to system assembly complexity, mass and, most importantly, cost. One of the most attractive possible features of a sandwich design - the integration of solar array with transmitting array into a single trivially deployable unit, may now be lost.

Further investigation of the insulating option is needed, however, to quantify these objections.

If selective reflectors are used to illuminate the solar cells on the sandwich with only light that they may efficiently convert, solar cell efficiency may approach the ratio of junction voltage to band gap voltage. This parameter is typically near .5, so $(1-\eta)^{-1}$ approaches 1. This value is down from $(1-\eta)^{-1} = 4$ for a conventional satellite design, but may never the less make for a solar power satellite with costs per unit installed power roughly equivalent to the reference klystron type satellites.

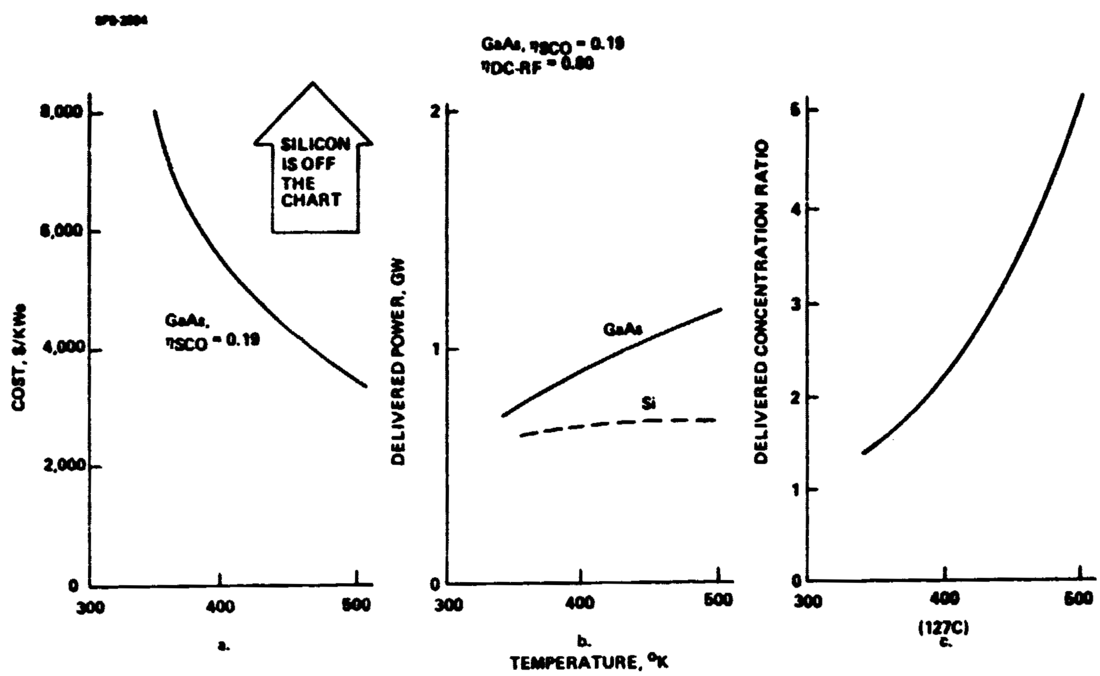


Figure 2. Performance vs Sandwich Temperature

Figure 3a shows cost and concentration ratio as a function of solar cell efficiency for both a selective concentrator satellite and a probably unrealistic, low-cost multiple band gap solar cell. The resulting geometry for the selectively concentrating satellite is shown in Figure 3b. Structural mass fraction changes for such drastic configuration stretchs were not explicity addressed. However, reflector masses and costs per unit area have a structural penalty added to them to allow simple first-order parametric analysis.

For environmental and microwave safety reasons all realistic power satellite system designs have some degree of transmitting array power taper. Sandwich satellites will not be an exception to this rule. Both options for the implementation of power taper (either conducting power radially inward in the sandwich plane or either shaping or cutting small holes in the reflectors) will raise costs an as yet unevaluated amount.

Figure 4, which shows initial power conductor mass, thickness and radial current for a reference 10-step Gaussian taper, indicates that voltages in the kilovolt range, substantially higher than 30 volts, are desirable for reasonable masses and costs. This is distressing in that it detracts from what may be the main potential advantages of a sandwich satellite - purely local power flow and power control at low voltages. The other option, power taper via reflectors, may be easier to implement. In either case, it is worth noting that there are radial power patterns which meet the first side lobe constraint (24.6 db down) and yet have a significantly greater average/peak power ratio than the reference 10-step Gaussian taper.

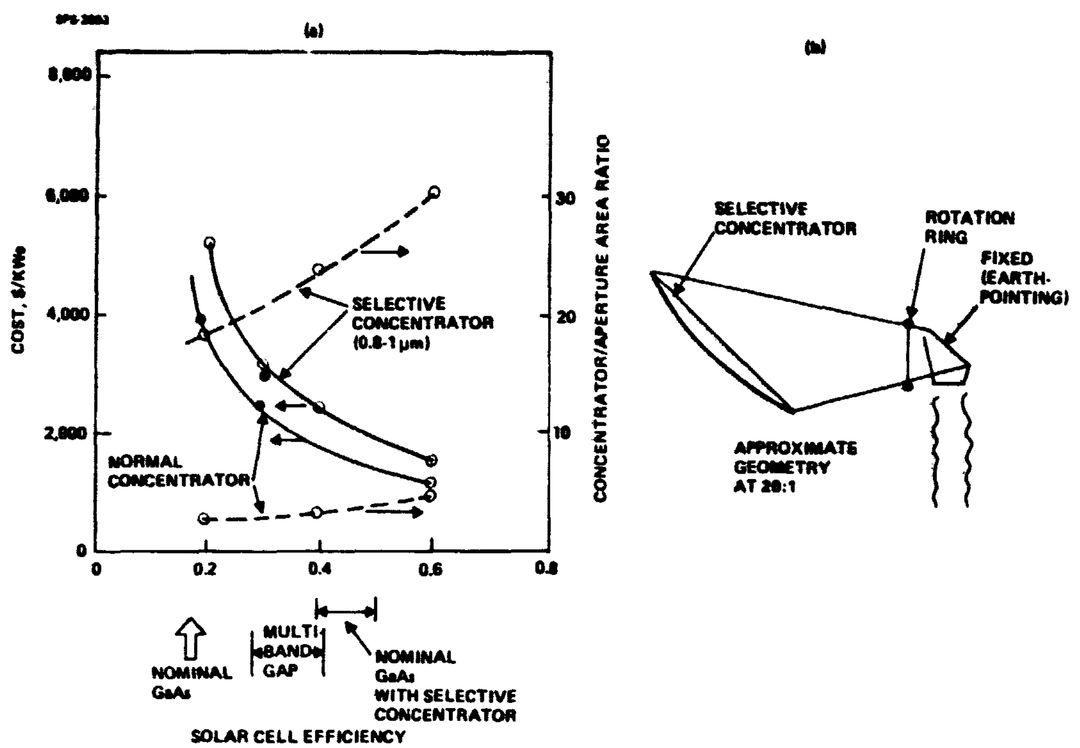


Figure 3. Performance vs Solar Cell Efficiency

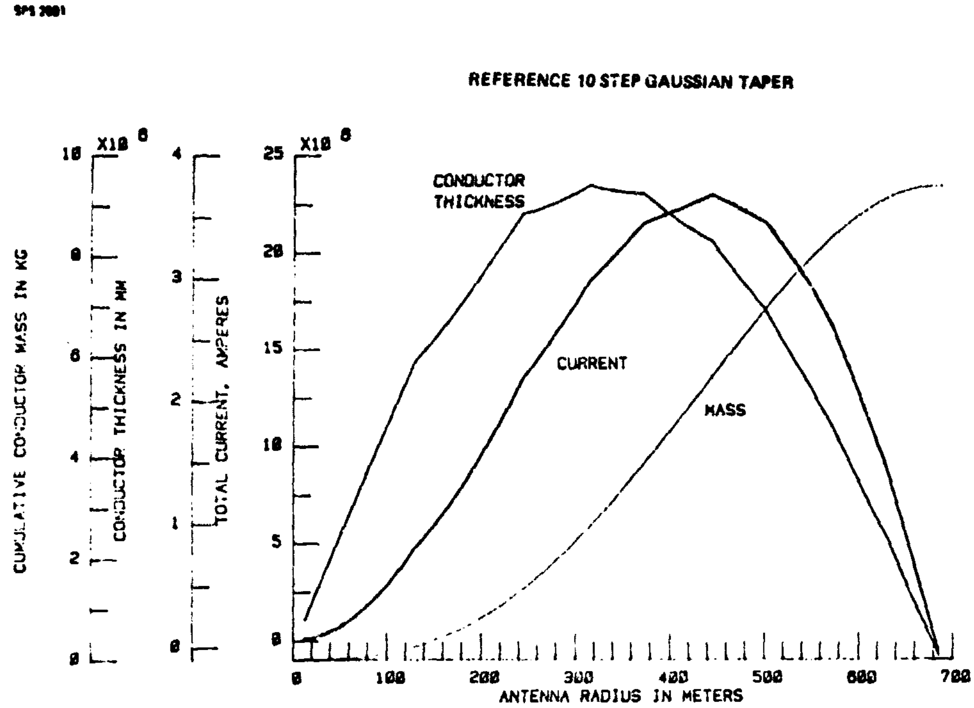


Figure 4.   30 Volt Power Conduction Results

PARAMETRIC DEVELOPMENT OF RELIABILITY DESIGN FOR A LARGE SOLAR POWER SATELLITE

This report presents the results of preliminary studies of reliability/availability design criteria for the conceptual design phase of a large Solar Power Satellite. The studies were limited to consideration of the amplifier arrays and treated individual amplifier reliability parametrically. The accurate treatment of success/failure logic and consequently array life for the baseline configuration (and variations) is a very complex matter. It is the author's feeling that this report represents a significant step in the development of overall understanding of this problem.

STATEMENT OF THE PROBLEM

Conceptual designs for a large Solar Power Satellite are being studied. The configurations of interest involve large arrays of GaAs FET amplifiers as the key mechanism for transmitting energy to the earth's surface. It is both desirable and necessary that the satellite, and consequently the amplifier array(s), be long-lived (upwards of 30 years). This requirement for long life dictates not only that the individual amplifiers be highly reliable, but also that the array(s) be configured such that the array availability remain high over the design life of the satellite. It has been generally accepted that the array availability - measured in terms of fraction of rated power output realized - should be greater than or equal to 0.98. The difficulty in accepting this figure as a design parameter lies in the inherent combinatorial complexity of the array(s) and consequently the difficulty in estimating the availability of various design options as a function of anticipated satellite life. It is this problem that the current study addresses. Parametric relationships are developed for array availability as a function of amplifier reliability and as a function of variations in the current baseline array configuration.

DEFINITIONS

Availability -

Generally, availability is defined as the fraction of time that an item (system) is performing its required function(s) or is capable of performing its required function(s). In this study availability (A) has been defined as the fraction of rated output surviving.

Reliability -

The probability that an item will perform as specified under specified environmental conditions for a specified period of time.

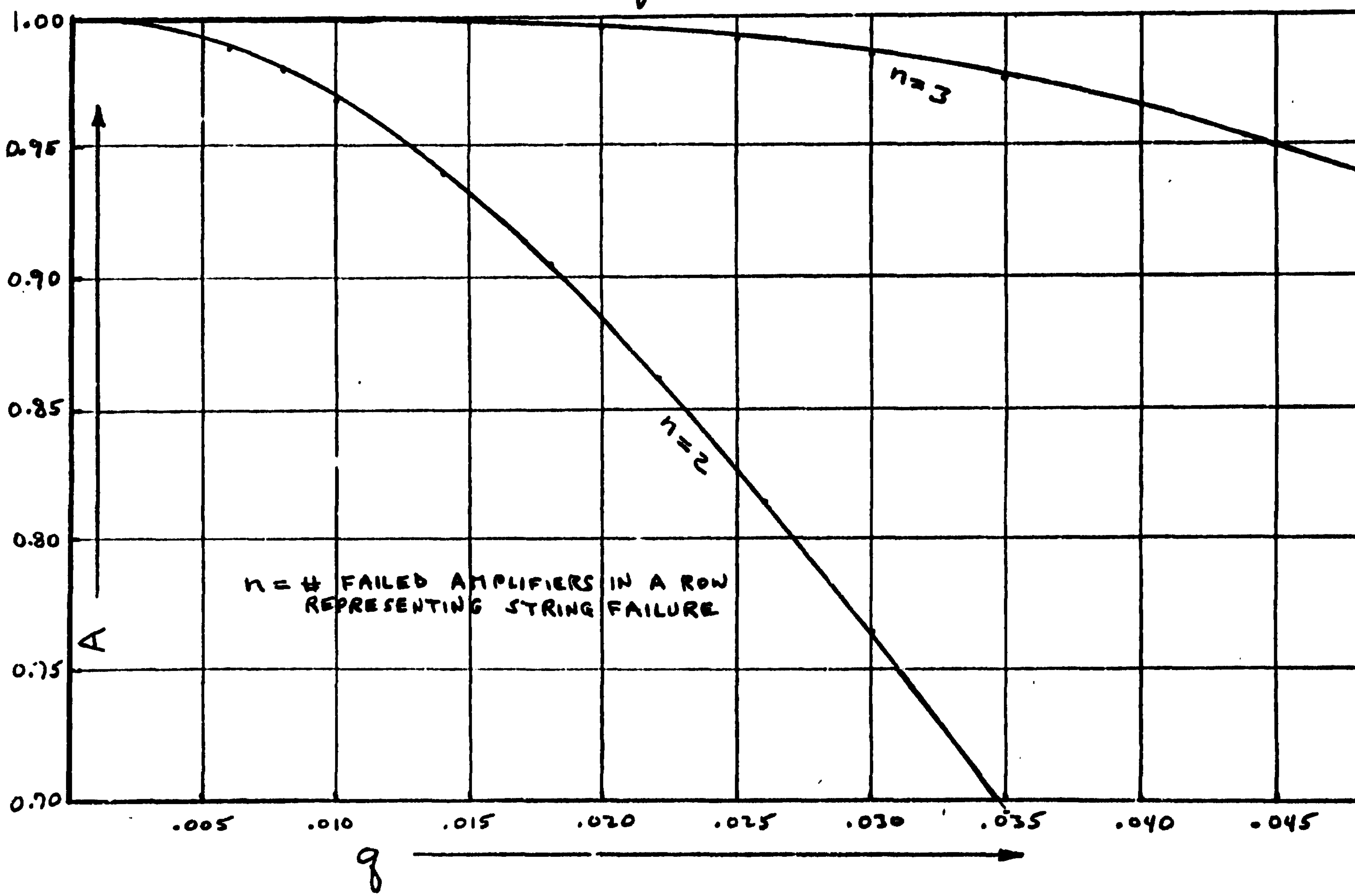
SUMMARY OF RESULTS AND CONCLUSIONS

The complexity of the baseline configuration, the state of definition of failure criteria and the limited time available for the study required that some approximations (described in later paragraphs) be made. However, it is the author's firm belief that these approximations resulted in very little error in the final relationships. It should be noted that this contention of small error has not been rigorously proved. In any case, these initial sets of relationships provide bounding criteria on expected life for given array configurations. It was determined in the course of this study that due to the large number of constituent amplifiers comprising a subarray, the subarray design criteria is essentially that of the array (or vice versa). In interpreting the relationships described herein, one must be cognizant of the analysis groundrules and assumptions and the underlying models (Ref: "Detailed Analysis").

Figure 1 portrays Fraction (A) of Subarray Output Surviving as a function of amplifier probability of failure (q). Curves are presented for both n=2 and n=3; where n is the number of amplifier failures in the same row allowed before a string failure occurs. Similar data for n=1 are presented in the Detailed Discussion.

The data of Figure 1 can be used as a basis for estimating Subarray A as a function of calendar time. This requires that amplifier reliability (1-q) be estimated as a function of time (t). This has been done parametrically

FIGURE 1. SUBARRAY A (FRACTION OUTPUT SURVIVING) versus q (AMPLIFIER PROB. OF FAILURE).



assuming that amplifier life-lengths are exponentially distributed. This amplifier life data is presented in Figure 2. Then the curves of Figure 1 were translated through the curves of Figure 2 yielding the parametric relationships of Figure 3. Subarray A versus Subarray Life in years is plotted parametrically in n and amplifier MTBF (θ). Again, this set of curves is valid only if the underlying life-length distribution for the amplifier is exponential (i.e., $q=1 - \exp(-t/\theta)$.

Several conclusions are readily apparent from the set of curves just discussed. First, the long-term Subarray Availability is very sensitive to Array configuration (i.e., value of n and length of string, etc.). Second, the baseline configuration - as described under "groundrules and assumptions" - would appear to support a 30-year availability goal of 0.98 only if $n=3$ and $\theta \geq 10^7$, or if $n>3$. Based on conventional reliability predictiontechniques an amplifier MTBF of 10^7 hours or greater appears to be very optimistic. However, there is a body of data to suggest that a log-normal life-length distribution is more appropriate than an exponential.

The models and data developed thus far provide a basis for further studies involving this design problem. Such studies should include:

Rigorous verification that the approximations of this study are valid;

Development of more comprehensive and universal availability models;

More detailed consideration of the system effect of amplifier failure modes;

Consideration of configurations different than the baseline - particularly with respect to string-length and row-width;

Consideration of the practicality of $n \geq 4$ in the baseline configuration;

More detailed study of FET amplifier reliability data - including consideration of log-normal distributions;

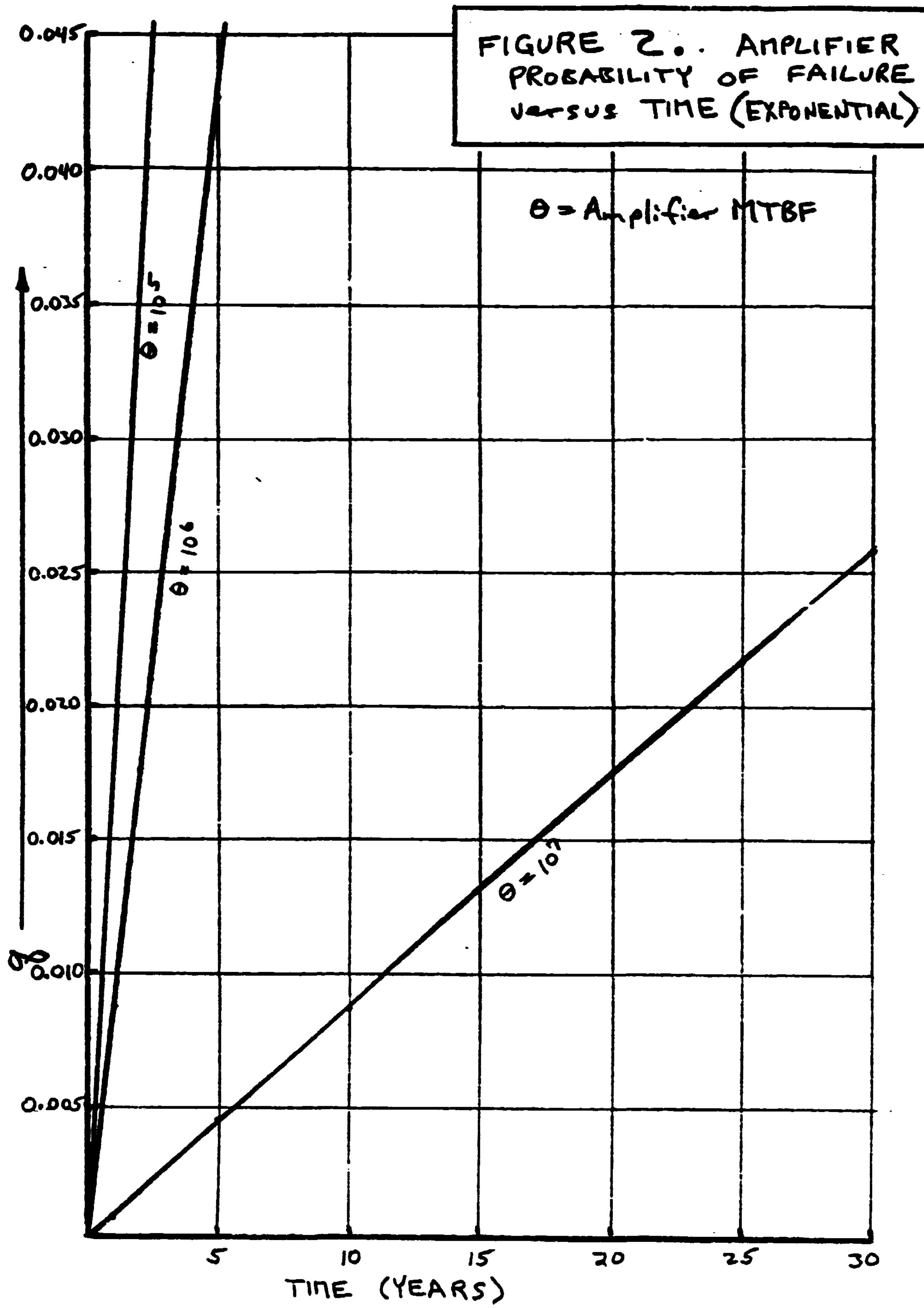
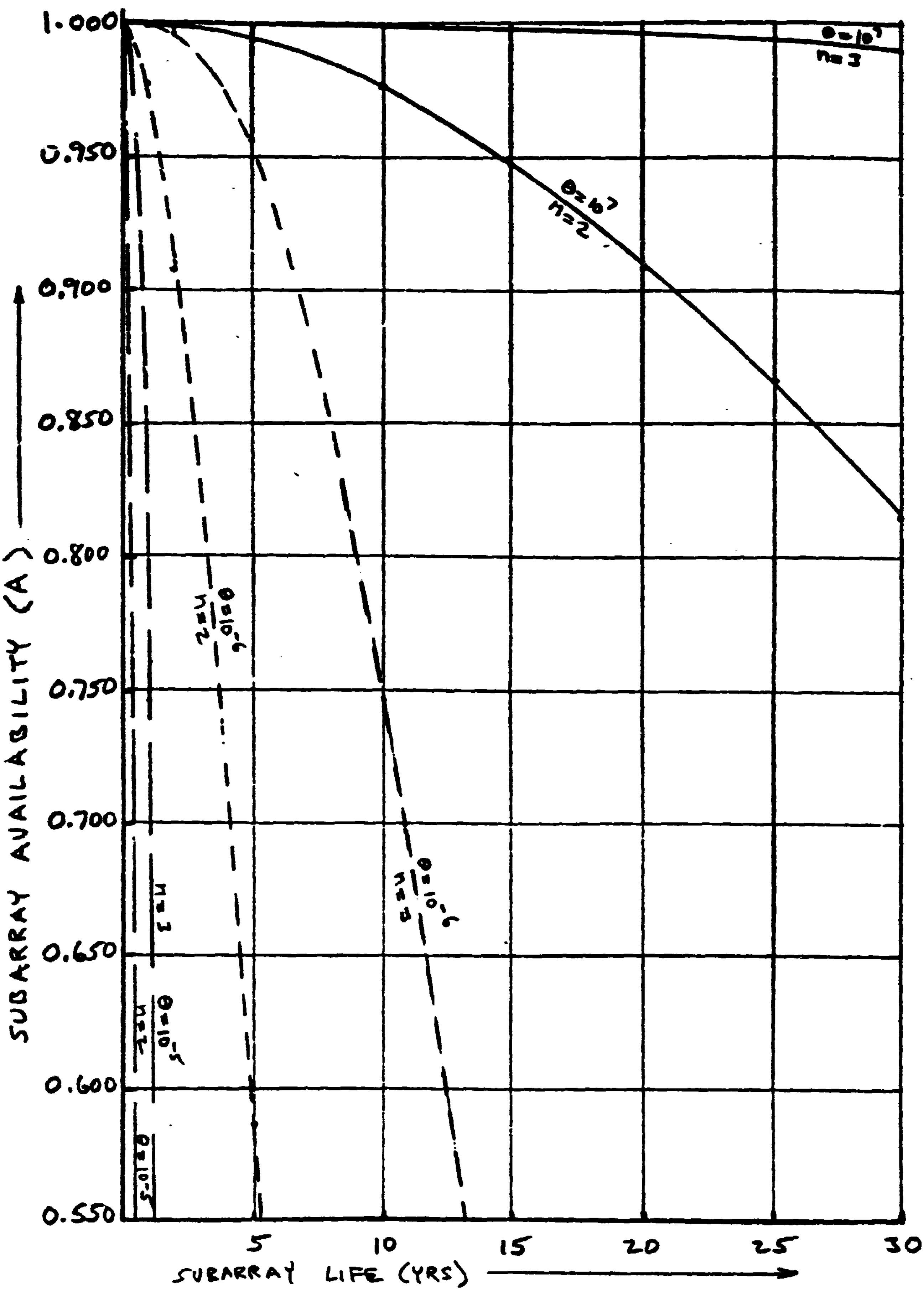


FIGURE 2. AMPLIFIER PROBABILITY OF FAILURE versus TIME (EXPONENTIAL)
θ = Amplifier MTBF
θ = 10^5
θ = 10^6
θ = 10^7
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
5
10
15
20
25
30
TIME (YEARS)

FIGURE 3. SUBARRAY A versus LIFE.



Use of these data to firmly bound design parameters and maximize configuration for availability.

ANALYSIS

The following paragraphs describe the details of this analysis. Assumptions and groundrules are presented along with the details of the evolution of the Subarray availability model. Various intermediate curves that were developed are also included. Tables of backup data associated with each of the curves are included at the end of this discussion.

GROUNDRULES & ASSUMPTIONS

The baseline configuration (system architecture or heirarchy) is that of a subarray consisting of a matrix of 12 panels by 12 panels; each panel consisting of 3 strings in parallel; each string comprised of 12 rows in series; and each row comprised of 4 modules in parallel where each module has a dual FET amplifier. This configuration is pictorially depicted in Figure 4.

In addition to the preceding definition of baseline configuration the following groundrules and assumptions pertain to this study:

(1) Each failed amplifier is assumed to operate at one-half power - as long as it is not in a "failed string";

(2) Each string failure results in no power output from that string;

(3) Design goal is that 2% degradation in Subarray power output represents failure.

DETAILS OF ANALYSIS

In order to understand the problem the Subarray availability model was developed in an evolutionary manner consisting of the following steps:

Step 1. A set of limiting curves was developed. This set of limiting curves was representative of a "Perfect Configuration" in which there

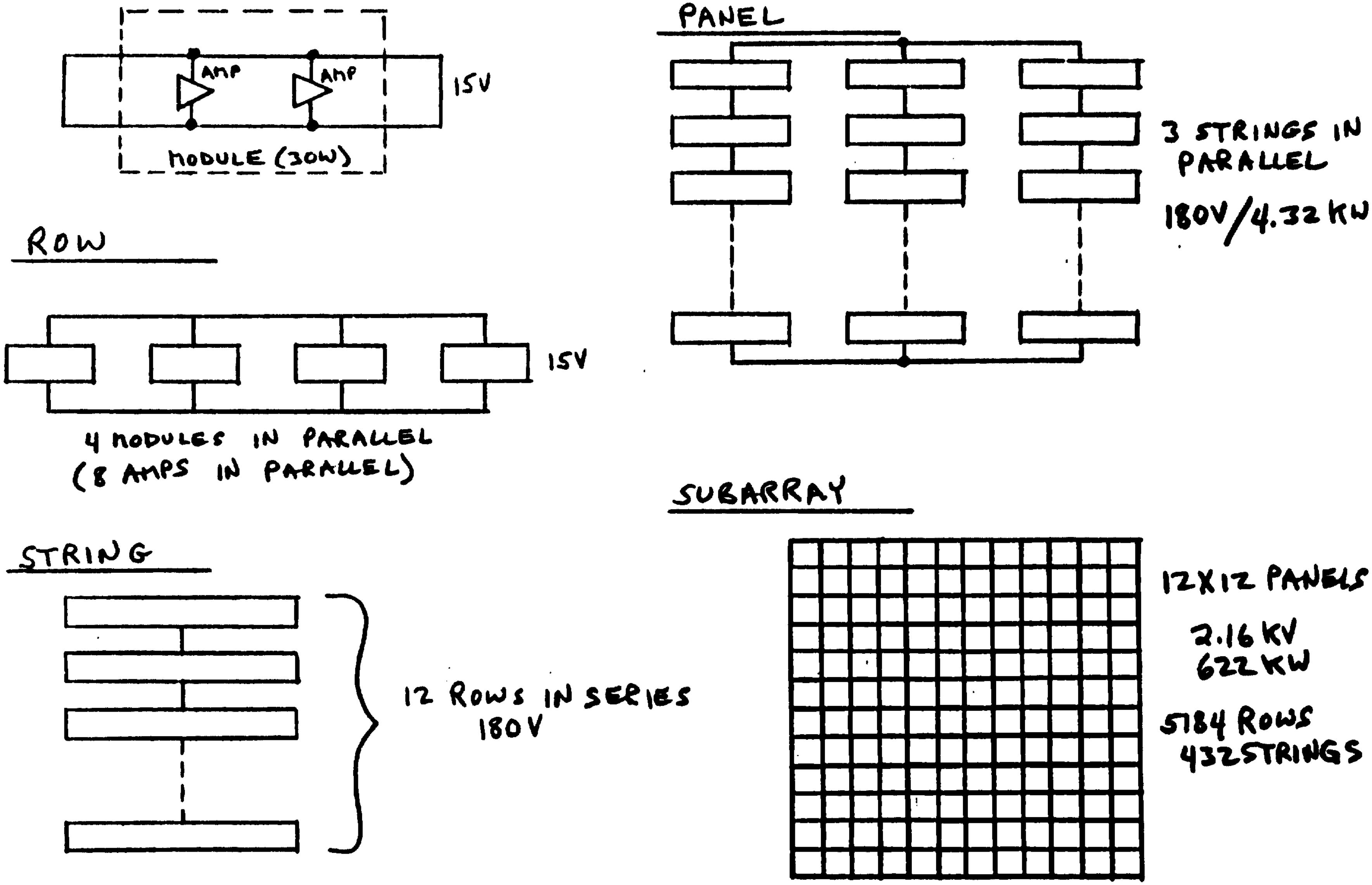


FIGURE 4. SUBARRAY BASELINE CONFIGURATION

could be no string failure. That is, the only effect of any combination of amplifier failures was to reduce the array output by an amount equal to one-half the amplifier output X the number amplifier failures. Another way of stating this condition is that there be no restriction on the location of amplifier failures as long as the maximum power degradation limit is not exceeded. In this case a 2% limit on degradation in Subarray Power .02(41472) (2) =
1659 failed amplifiers is the threshold for Subarray failure. The probability of Subarray failure can thus be determined as follows:

$$\text{Prob}\ \{1659 \text{ failures or more out of } 41472\} = Q^*_{S/A}$$

$$Q^*_{S/A} = \sum_{i=1659}^{41472} \binom{41472}{i} q^i p^{41472-i}$$

$$= 1 - \sum_{i=0}^{1658} \binom{41472}{i} q^i p^{41472-i}$$

Where p = Amplifier Reliability
q = 1-p = Prob. of Amplifier Failure

This cumulative binomial involves such large n and i that it is readily and accurately evaluated by approximating it with a normal distri- bution where:

$$\mu = nq = 41472q$$
$$\sigma^2 = npq = 41472\,p\,q$$

Similarly, relationships for degradation thresholds of 1% and of 3% were derived. These resultant curves are plotted in Figure 5.

Step 2. Consideration was given to the effect of string failure. String failure criteria (n = 2, and n = 3) and associated string failure models

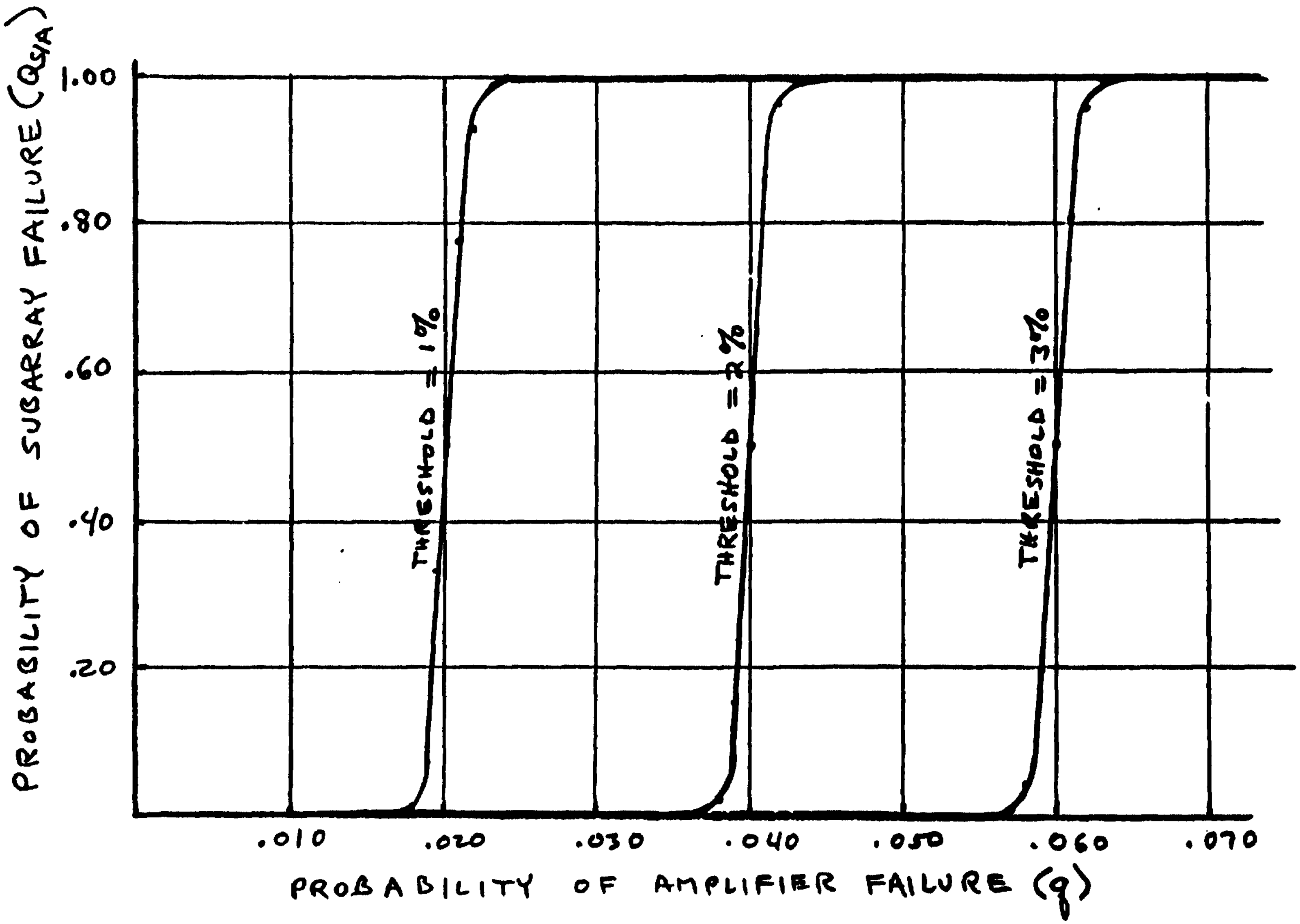


FIGURE 5. $Q_{S/A}$ versus q – "PERFECT CONFIGURATION"

are summarized in Table 1. These models were used to evaluate the probability of string failure (Q_s) over a range of possible amplifier probabilities of failure (q) for both n = 2 and n = 3. The results are shown in Figure 6.

Step 3. Modifications were made to the "perfect configuration" model of step one to account for Subarray degradation due to loss of strings. There are 432 strings in a Subarray. Thus if we assume that a string failure implies that there is no power output from that string, then:

Each string lost = 1/432 Degradation;
2% Threshold $\geq$ 9 Strings Failed.

Thus a model was structured as a set of "conditional events" representing the occurrence of a particular number of string failures (A_i) in conjunction with the occurrence of a quantity (B_i) of failed amplifiers that exceeds the conditional threshold associated with the number of failed strings. The elements of this model are summarized in Table 2. The general statement of this model is:

$$Q_{S/A} = \sum_{i=\phi}^{9} A_i B_i$$ where A_i and B_i are defined in Table 2.

Figure 7 depicts the relationship between Subarray probability of failure ($Q_{S/A}$) and amplifier probability of failure (q) for n=1 and for n=2. Note that for n = 1 the string probability of failure $Q_s = 1-p^8$. Further, it can be noted that in the range of n that we are considering for the baseline configuration the string failure contribution generally "swamps out" individual amplifier contribution to subarray failure.

Step 4. A model of Subarray degradation versus amplifier unreliability (q) was developed. This model in turn provided the basis for depicting

TABLE 1.
STRING RELIABILITY MODEL(S)

BASELINE MODEL (n=2)

FAILURE CRITERIA - 2 OR MORE AMPLIFIERS IN ONE ROW FAILED CONSTITUTE STRING FAILURE. (MAXIMUM NUMBER OF FAILURES ALLOWED PER ROW IS 2 (n=2) FOR STRING SUCCESS).

MATHEMATICAL MODEL

$$Q_s = 1 - (p^8 + 8p^7q)^{12}$$

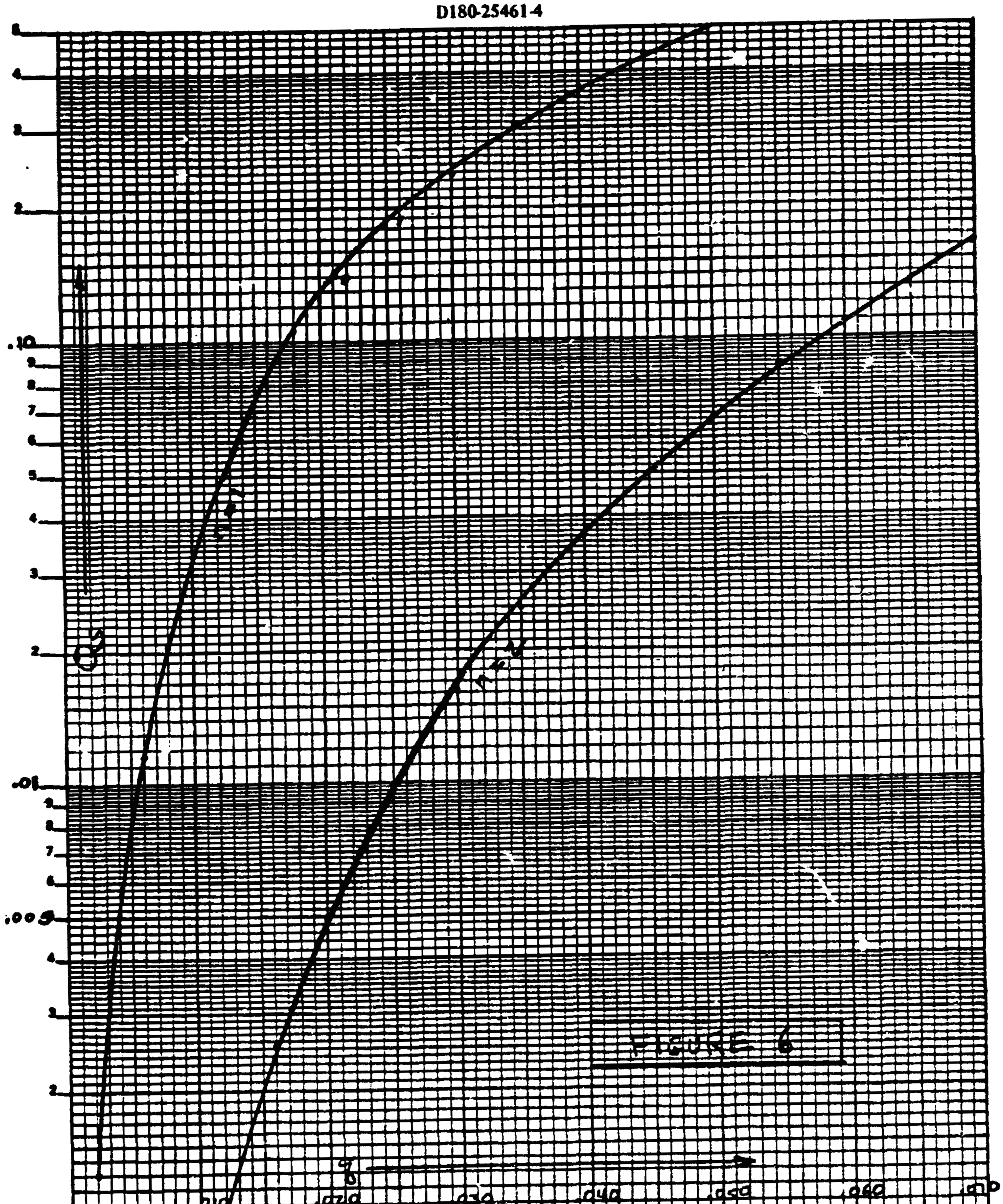
Where p = Amplifier Reliability
q = 1-p

ALTERNATE MODEL (n=3)

FAILURE CRITERIA - 3 OR MORE AMPLIFIERS IN ONE ROW FAILED CONSTITUTE STRING FAILURE. (n=3)

MATHEMATICAL MODEL

$$Q_s = 1 - (p^8 + 8p^7q + 28p^6q^2)^{12}$$



CALC	[illegible]	3/16/9	REVISED	DATE	STRING UNRELIABILITY (Q_S) VS. AMPLIFIER UNRELIABILITY (q)	
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(i)	A		B
(0)	$(1 - Q_S)^{432}$	X	$\sum_{1658}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(i)	$432(1 - Q_S)^{431}Q_S$	X	$\sum_{1466}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(2)	$\binom{432}{2}(1 - Q_S)^{430}Q_S2$	X	$\sum_{1274}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(3)	$\binom{432}{3}(1 - Q_S)^{429}Q_S^3$	X	$\sum_{1082}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(4)	$\binom{432}{4}(1 - Q_S)^{428}Q_S^4$	X	$\sum_{890}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(5)	$\binom{432}{5}(1 - Q_S)^{427}Q_S^5$	X	$\sum_{698}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(6)	$\binom{432}{6}(1 - Q_S)^{426}Q_S^6$	X	$\sum_{506}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(7)	$\binom{432}{7}(1 - Q_S)^{425}Q_S^7$	X	$\sum_{314}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(8)	$\binom{432}{8}(1 - Q_S)^{424}Q_S^8$	X	$\sum_{122}^{5184} \binom{5184}{j}(8qp^7)^j(p^8)^{5184-j}$
(9)	$\sum_{i=9}^{432} \binom{432}{i}(1 - Q_S)^{432-i} Q_S^i$	X	1

i = # FAILED STRINGS

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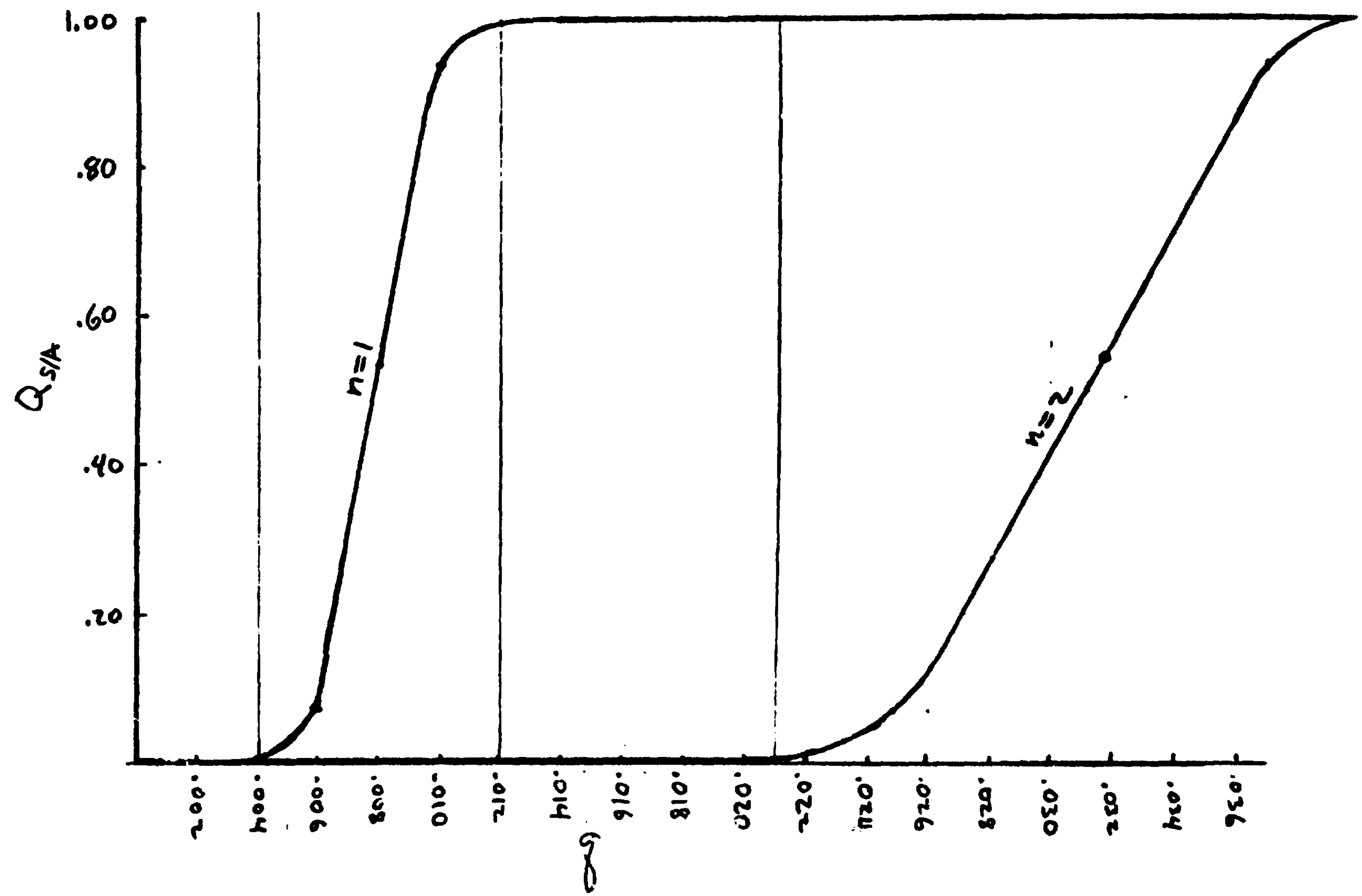

FIGURE 7. SUBARRAY PROBABILITY OF FAILURE ($Q_{S/A}$) VS. AMPLIFIER PROBABILITY OF FAILURE (q).

Subarray degradation versus time as described in the summary of results. As a preliminary approach, only the A_i segment of the subarray availability model was used (Ref: Table 2). As an approximation it was assumed that no appreciable contribution accrued from the B_i segments. (Since we are no longer interested in just exceeding a given threshold (e.g., 2%) of degradation. The table of A_i versus Q_s was enlarged. A fraction degradation (D_i) was associated with each A_i and the expected degradation (total) for each Q_s was calculated thusly:

$$\overline{D_T} = \sum_{i=1}^{432} A_i D_i \text{ where } D_i = \frac{i}{432}$$

The expected fraction survi .ng (A) can be estimated as: $A = 1 - D_T$. q is then related to Q_s and consequently A for n = 2 and n = 3, as plotted in Figure 1. Ultimately, A can be plotted against time because q is a function of time (e.g., exponential).

POWER DISTRIBUTION SYSTEMS ANALYSIS FOR 2.5 GW SPS (SOLID STATE MPTS)

Introduction

The concepts being analyzed for the all solid-state microwave power distribution system require power delivered in the 2 kv to 5 kv voltage range. Three methods of delivering power to the antenna which were investigated are as follows:

1. Acquire power from the array at approximately 44 kv and use ac/dc converters on the antenna to derive the required voltage levels to supply the antenna solid state devices.

2. Acquire power from the array at about 11,000 volts, convert to ac at the array and back to dc at the antenna.

3. Acquire power from the array at about 5,500 volts and supply the antenna solid state devices directly from the array without any power processing.

The following paragraphs summarize the results of this analysis.

44 KV System

This concept is similar to that used on the Reference 5 GW SPS which uses klystrons as the dc to RF converters. The exception is that instead of processing only about 15% of the power all power is processed. The mass penalty for processing all power is approximately 1.59 kilograms for each kilowatt of processed power as shown in Table 1 at a chopping frequency of 20 kilohertz. Dc/dc converter losses represent 5.56% of the input power (ref. Table 1).

The power distribution system mass and power loss summary for the 44 kv system is shown in Table 2. The entry "non-P-max power loss penalty" is due to the fact that all solar cell strings are not operating at the peak power point. Figure 1 shows the relationship of normalized string voltage to normalized string current and power. For the 44 kv case and with a conductor operating temperature of 100°C, the power loss is small (about 0.5%). However, as will be seen later in the low voltage case, this is not always the case.

For the 44 kv case, the total current required by the antenna is 109,484 amperes. For one millimeter thick aluminum conductors the total width of the positive or negative conductors is 17.3 meters.

AC Power Distribution System

The ac power distribution system analyzed consisted of acquiring power from the array at a nominal voltage of 11 kv, converting to ac at the power sector level, transmitting the ac power to the antenna on the main power bus, and converting back to dc power at the proper voltage level on the antenna.

The dc to ac and ac to dc converter mass and losses were derived from the dc/dc converter used in the 44 kv analysis above and are shown in Table 3 and Table 4, respectively. Additional filtering was added for the ac output.

The selection of the operating frequency was based on two criteria: minimizing converter mass, and minimizing skin effects. Figure 2 shows converter mass (ac/dc plus dc/ac) as a function of chopping frequency. Table 5 shows the result of the skin effect analysis. Based on these two analysis, the selected operating frequency for the ac system was 10 kilohertz. This frequency minimizes skin effect losses for one millimeter thick conductors while incurring a slight penalty in the masses of the converters.

The main bus operating voltage was selected to be 100 kv nominal. There is negligible array power loss due to not operating at the maximum power point of the cell-string since each dc to ac converter can be designed to track the maximum power point.

The results of the ac power distribution system analysis is summarized in Table 6. The total mass of the array and power distribution system for the ac system is slightly higher than for the 44 kv dc system described above. The primary contributors to this increase in mass over the 44 kv dc system with 100% power processing is the additional filtering of the ac at the dc to ac converter and the requirement to use transformers at both the dc to ac and the ac to dc converters. The efficiency of the ac system is higher than that of the 44 kv dc system primarily because of reduced main bus losses when operating at the higher voltage with with ac system.

For the ac 100 kv system, the total current required by the antenna is 45,748 amperes. For the one millimeter thick conductors the total width of the positive or negative conductors is 7.23 meters.

Low Voltage DC Power Distribution System

The low voltage power distribution system which was analyzed acquires power from the satellite across one bay width (array voltage 5,500 V nominal) of solar array and delivers it to the antenna mounted dc to rf converters without any intervening power processing. In order to deliver 4,300 megawatts of power to the dc to rf converters from this low supply voltage, the current required is in the order of one million amperes.

Of particular significance in this low voltage case is the voltage drop of the conductors which determines the operating point on the solar cell string V/I curve. For this low voltage case most of the array will be operating at points which are at reduced power levels compared to the maximum power point. This is summarized in Table 7 and shows that at higher design operating temperatures for the conductors a significant portion of the available array power is not being advantageously used. Figure 3 shows the percentage of power loss as a function of conductor design operating temperature.

For the sheet conductors used in the SPS studies to date, at a given design operating temperature and current level, the conductor losses are inversely proportional to the square root of the conductor thickness and the mass of the conductor is directly proportional to the square root of the conductor thickness. At the current levels required for the low voltage distribution system to supply 4,300 megawatts to the antenna sheet conductor total width (the sum of the widths of all positive or return power buses) is in the order of 221 meters at 50°C. Increasing the conductor thickness to two millimeters from one millimeter decreases the conductor width to 157 meters and increases the conductor mass from 3,570 metric

tons to 5,048 metric tons for the main power buses. The conductor losses would be reduced from 1,170 megawatts to 827 megawatts.

Sheet conductor sizing for the SPS power distribution system is accomplished using the curve shown in Figure 4. For a given operating temperature a point, K, can be obtained from the curve such that

$$\frac{I}{W\sqrt{t}} = K \qquad (1)$$

where I = Current in amperes
W = Conductor width in centimeters
t = Conductor thickness in centimeters

on a per meter basis, resistance (R) is given by

$$R = \rho \frac{L}{A} = \rho \frac{100}{Wt} \quad (2)$$

where ρ = resistivity of a aluminum (3.43×10^{-6})

but from (1)

$$W = \frac{I}{K\sqrt{t}}$$

so that

$$R = \frac{\rho\, 100}{\frac{I}{K\sqrt{t}}\,t} = \frac{100\, K\rho}{I\sqrt{t}} \quad (3)$$

and voltage drop = IR = $\dfrac{100\, K\rho I}{I\sqrt{t}} = \dfrac{100 K\rho}{\sqrt{t}}$ (4)

For aluminum sheet material on a per meter basis

Mass = σ W t L = 100 σ Wt

where σ = Specific weight in kilograms per cm^3 (0.0027 for aluminum)

but from (1)

$$W = \frac{I}{K\sqrt{t}}$$

and mass in kilograms/meters of length

$$= (100)(0.0027) \quad \frac{I}{K\sqrt{t}}\,t$$

$$= \frac{0.27}{K}\, I\sqrt{t} \qquad (5)$$

From equation 4 it can be seen that (for a given operating temperature and current level) increasing the thickness reduces the per-unit-length voltage drop (and thus I^2R losses) by the square root of the thickness but conductor mass is increased, as shown in equation 5, by the square root of the thickness. The least mass system is to make the conductor as thin as possible. A thickness of one millimeter was selected primarily to prevent damage during the construction process if thinner material were used.

For the analysis discussed in this section one millimeter thick sheet conductors were used. The results of the low voltage analysis for various operating temperatures is summarized in Table 8. The system mass and losses were computed for several conductor design operating temperatures to determine the minimum mass system.

Results and Conclusion

The results of the three analysis in terms of the total of required array mass plus power distribution system mass is graphically shown by Figure 5. The minimum mass system occurs with the low-voltage/no-power-processing concept operating at a conductor operating temperature of about 35°C. If conductor width is of concern other options are available which significantly reduce the required width with a modest increase in system mass.

TABLE 1
DC/DC CONVERTER SUMMARY
(5,600 KW)

Element		MASS (KG) 1KHZ	10KHZ	20KHZ	30KHZ	LOSSES (KW) 1KHZ	10KHZ	20KHZ	30KHZ
Input Filter		1,535	768	570	528	30	42	48	54
Switching	Cond	575	575	575	575	12	12	12	12
	SW					2.4	12	24	36
Drive and Suppression		112	86	78	70	2.2	5.5	11	16.5
Transformer		1,436	348	170	125	70	70	70	70
Rectifier		226	226	226	226	2.2	2.2	2.2	2.2
Output Filter		4,780	2,303	1,733	1,587	60	120	138	149.5
Packaging		2,599	1,292	1,006	933	-	-	-	-
Thermal Control		2,663	3,927	4,545	5,066	3.6	5.3	6.1	6.8
Total		13,926	9,525	8,903	9,110	182.4	269.0	311.3	347.0
Per Kilowatt Values		2.487	1.701	1.590	1.627	0.0326	0.0480	0.0556	0.0620

TABLE 2
DC POWER DISTRIBUTION - 44 KV
2.5 GW SATELLITE, 100% POWER PROESSING
Tc = 100°C
DELIVERED POWER = 4,300 MW TO DC/RF CONVERTERS

System Element	Mass In Metric Tons	Losses In Megawatts
Non-P-Max Power Loss Penalty	-	24.2
Acquisition Buses	19.8	11.3
Main Buses	401.0	264.1
Switchgear	85.7	-
DC/DC Converters	7,239.6	253.2
Total	7,746.1	552.8
Array Power (MW)	4,852.8	
Array Area (KM^2)	29.09	
Array Mass (MT)	12,356.0	
System Efficiency =	88.6%	
Mass (Array + Pwr. Dist)(MT)	20,102.1	

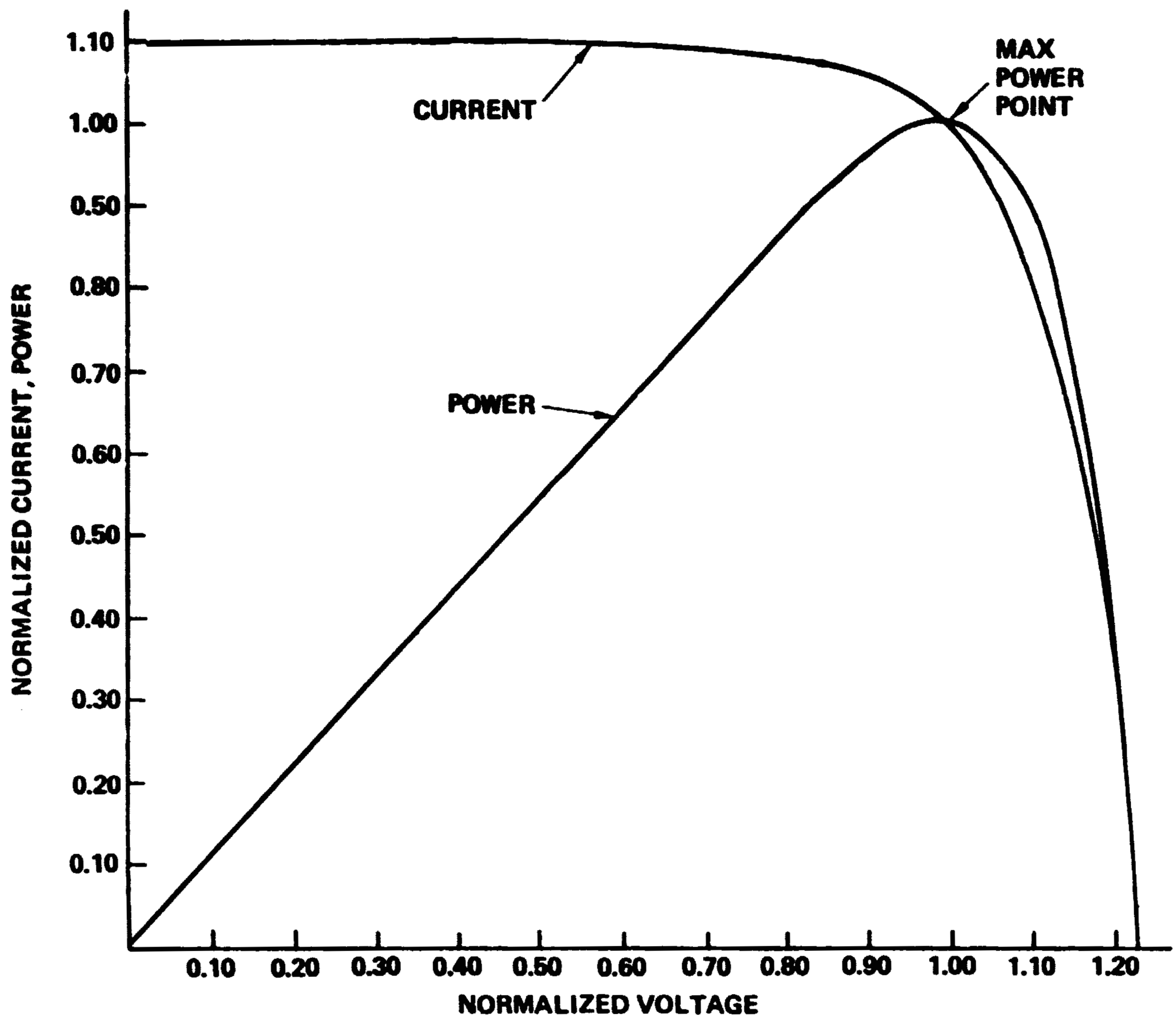

Figure 1: Normalized Cell String Parameters

TABLE 3
DC/DC CONVERTER - 5600 KW

Element		MASS (KG) 1KHZ	MASS (KG) 10KHZ	MASS (KG) 20KHZ	MASS (KG) 30KHZ	LOSSES (KW) 1KHZ	LOSSES (KW) 10KHZ	LOSSES (KW) 20KHZ	LOSSES (KW) 30KHZ
Input Filter		1,535	768	570	528	30	42	48	54
Switching	Cond	575	575	575	575	12	12	12	12
	SW					2.4	12	24	36
Drive and Suppression		112	86	78	70	2.2	5.5	11	16.5
Transformer		1,436	348	170	125	70	70	70	70
Output Filter		478	230	173	159	6	12	14	15
Packaging		1,248	613	502	459	-	-	-	-
Thermal Control		1,826	2,257	2,667	3,032	2.4	3.0	3.6	4.1
Total		7,210	4,877	4,736	4,948	125.0	154.5	182.6	207.6
Per Kilowatt Values		1.288	0.871	0.846	0.884	0.0223	0.0276	0.0326	0.0371

TABLE 4
AC/DC CONVERTER VALUES
(5600 KW)

Element	MASS (KG) 1KHZ	10KHZ	20KHZ	30KHZ	LOSSES (KW) 1KHZ	10KHZ	20KHZ	30KHZ
Transformer	1,436	348	170	125	70	70	70	70
Rectifier	226	226	226	226	2.2	2.2	2.2	2.2
Output Filter	4,780	2,303	1,733	1,587	60	120	138	149.5
Control Circuitry	10	10	10	10	.2	.2	.2	.2
Packaging	1,947	871	645	588	-	-	-	-
Thermal Control	1,973	2,867	3,135	3,306	2.6	3.8	4.2	4.4
Total	10,372	6,625	5,919	5,842	135.0	196.2	214.6	226.3
Per Kilowatt Values	1.852	1.183	1.057	1.043	0.0241	0.0350	0.383	0.0404

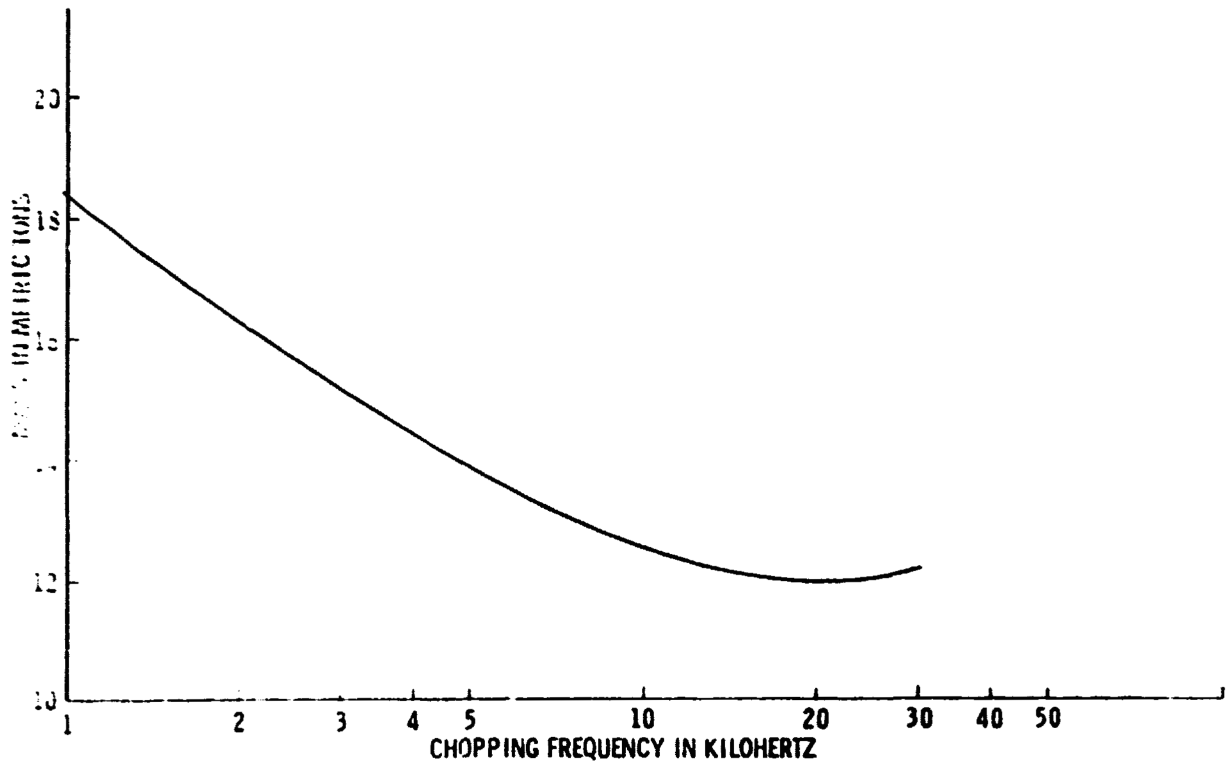

Figure 2: AC Power Distribution System Frequency Optimization

TABLE 5
SKIN EFFECT IN SHEET CONDUCTORS

$$\delta = \frac{1}{\pi u \sigma f}$$

For Aluminum

$\mu = 4 \times 10^{-7}$ henry/meter

$\sigma = 3.72 \times 10^{7}$/ohm-meter

$\delta =$ skin depth in meters

Skin depth is that distance below the surface of a conductor at which the current has reduced to 1/e of its value at the surface due to the inductive reactance of the conductor.

Solving for skin depth versus frequency for aluminim yields the following results:

Frequency (Hertz)	Skin Depth (Millimeters)
100	8.26
500	3.69
1,000	2.61
5,000	1.17
10,000	0.826
20,000	0.584
30,000	0.477

TABLE 6
AC POWER DISTRIBUTION SUMMARY
2.5 GW SATELLITE, FREQUENCY = 10 KHZ, $T_c = 100^oC$
OPERATING VOLTAGES ARRAY 11 KV MAIN BUS 100 KV

System Element	Mass (MT)	I^2R Loss (MW)
Non-P-Max Power Loss Penalty	-	-
Acquisition Buses	19.7	46.0
DC/AC Converters	4,146.5	135.2
Main Buses	257.2	115.0
Switchgear	203.3	-
AC/DC Converters	5,175.9	164.4
Total	9,802.6	460.6

Array Power = 4,760.6 MW
System Efficiency = 90.3%
System Losses = 9.7%
Array Area = 28.53 KM^2
Array Mass = 12,119.0

Mass (Array + Pwr Dist) = 21,921.6 MT

TABLE 7
ARRAY OPERATING EXTREMES VS CONDUCTOR DESIGN OPERATING TEMPERATURE

Conductor Design Operating Temp. In Degrees C	Normalized Array Operating Voltage: Power Sector Nearest To Antenna	Normalized Array Operating Voltage: Power Sector Farthest From Antenna	Normalized Array Power Point Operation: Power Sector Nearest To Antenna	Normalized Array Power Point Operation: Power Sector Farthest From Antenna	Average Array Power Point
0	.941	1.060	.980	.955	.990
25	.887	1.119	.938	.838	.973
50	.776	1.124	.842	.823	.955
100	.580	1.150	.630	.765	.863

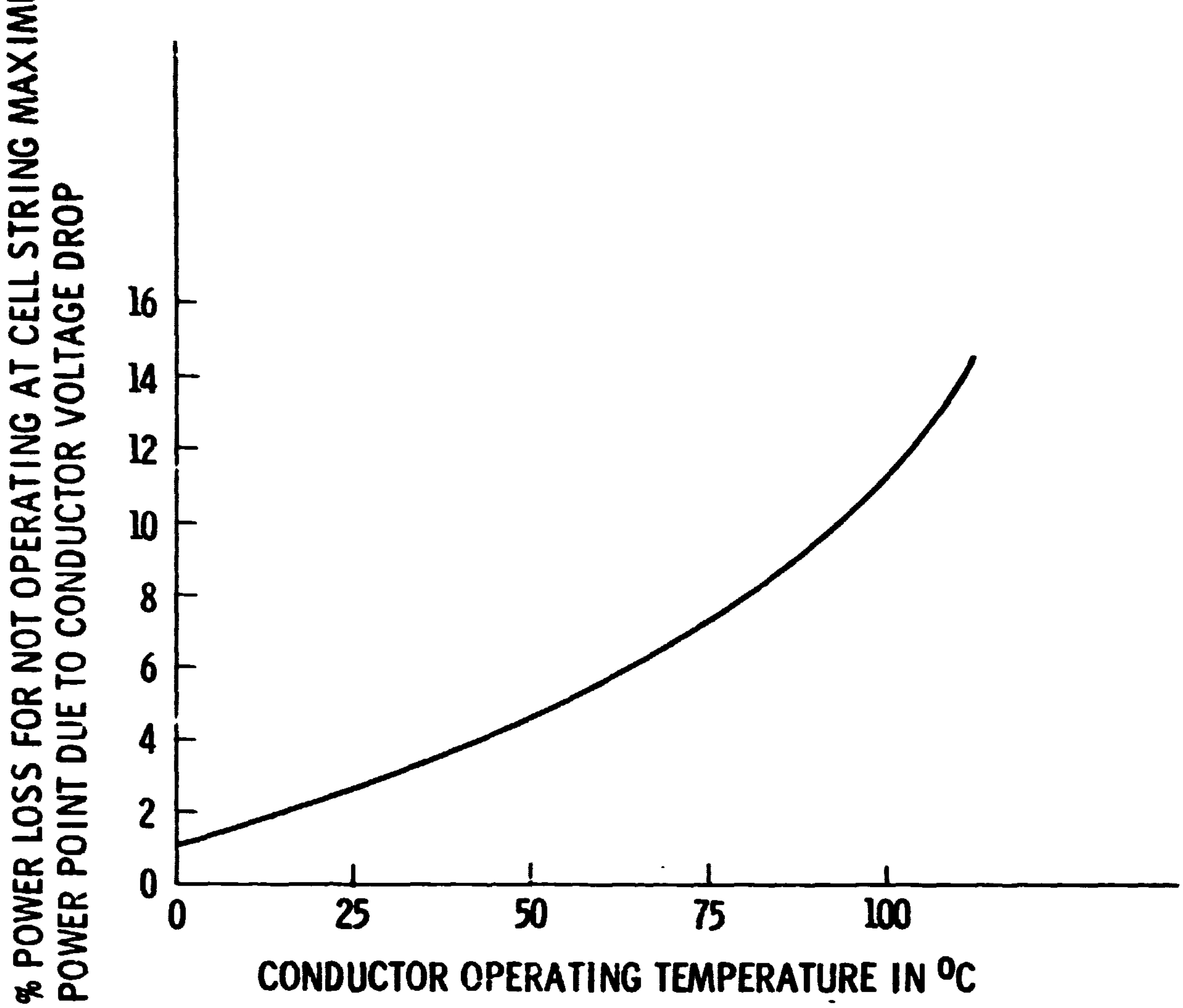

Figure 3: 2.5 GW Solid State SPS Configuration Cell String Voltage = 5,500 V.

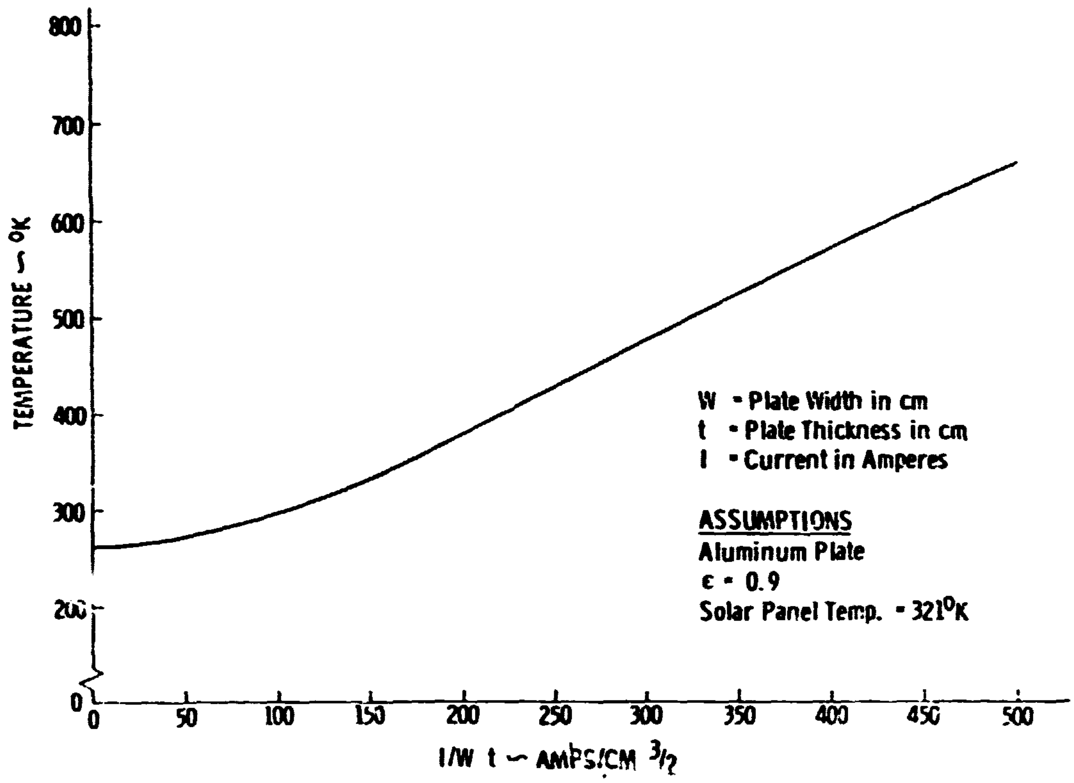

Figure 4: SPS Energy Conversion Power Bus Sizing

TABLE 8
DC POWER DISTRIBUTION - LOW VOLTAGE
2.5 GW SATELLITE, ARRAY OPERATING VOLTAGE 5,500V (NOM)
DELIVERED POWER = 4,300 MW TO DC/RF CONVERTERS

	Mass In Metric Tons Conductor Temp°C				Power Loss In Megawatts Conductor Temp°C			
System Element	0	25	50	100	0	25	50	100
Non-P-Max Power Loss Penalty	-	-	-	-	96.6	150.8	272.6	1,114.2
Acquisition Buses	582.4	330.8	249.2	191.9	17.3	37.4	58.9	132.9
Main Buses	7,19810	4,385.9	3,570.3	3,588.4	416.0	899.2	1,169.5	2,836.4
Switch Gear	147.4	153.1	157.2	183.3	-	-	-	-
TOTAL	7,927.8	4,869.8	3,976.7	3,963.6	529.9	1,087.4	2,501.0	4,083.5
Array Area KM^2	28.95	32.39	34.77	50.43				
Array Power Avail (GW)	4,829.9	5,387.4	5,801.0	8,413.5				
Array Mass (MT)	12,297.4	13,758.6	14,769.6	21,421.6				
Delivered Power V	5,015	4,523	4,104	2,932				
(To DC/RF Converters) I	857,462	919,983	994,450	1,297,525				
Mass (Array + Pwr Dist)	20,225.2	18,628.4	18,746.3	25,385.2				

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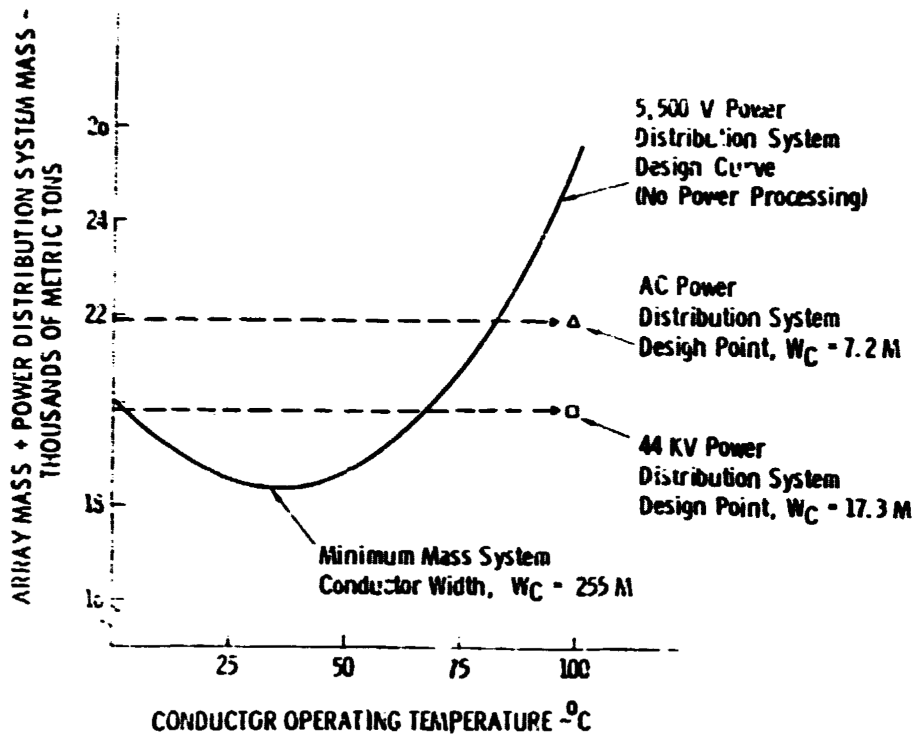


Figure 5: Power Distribution System Analysis for 2.5 GW SPS

MULTIBEAM SPS STUDY

Introduction

The possibility of transmitting several power beams from an SPS has intrigued various researchers at Boeing (and undoubtedly elsewhere) for some time. Recently some computer runs were made to verify the capability of transmitting multiple beams using a modified version of the large array program TILTMAIN.

The scheme used to generate the beams was the simplest possible one imagineable, namely splitting the main beam along an axis by spatially modulating the illumination function by a factor cos (k r sin θ) when:

$k = 2\pi/\lambda$

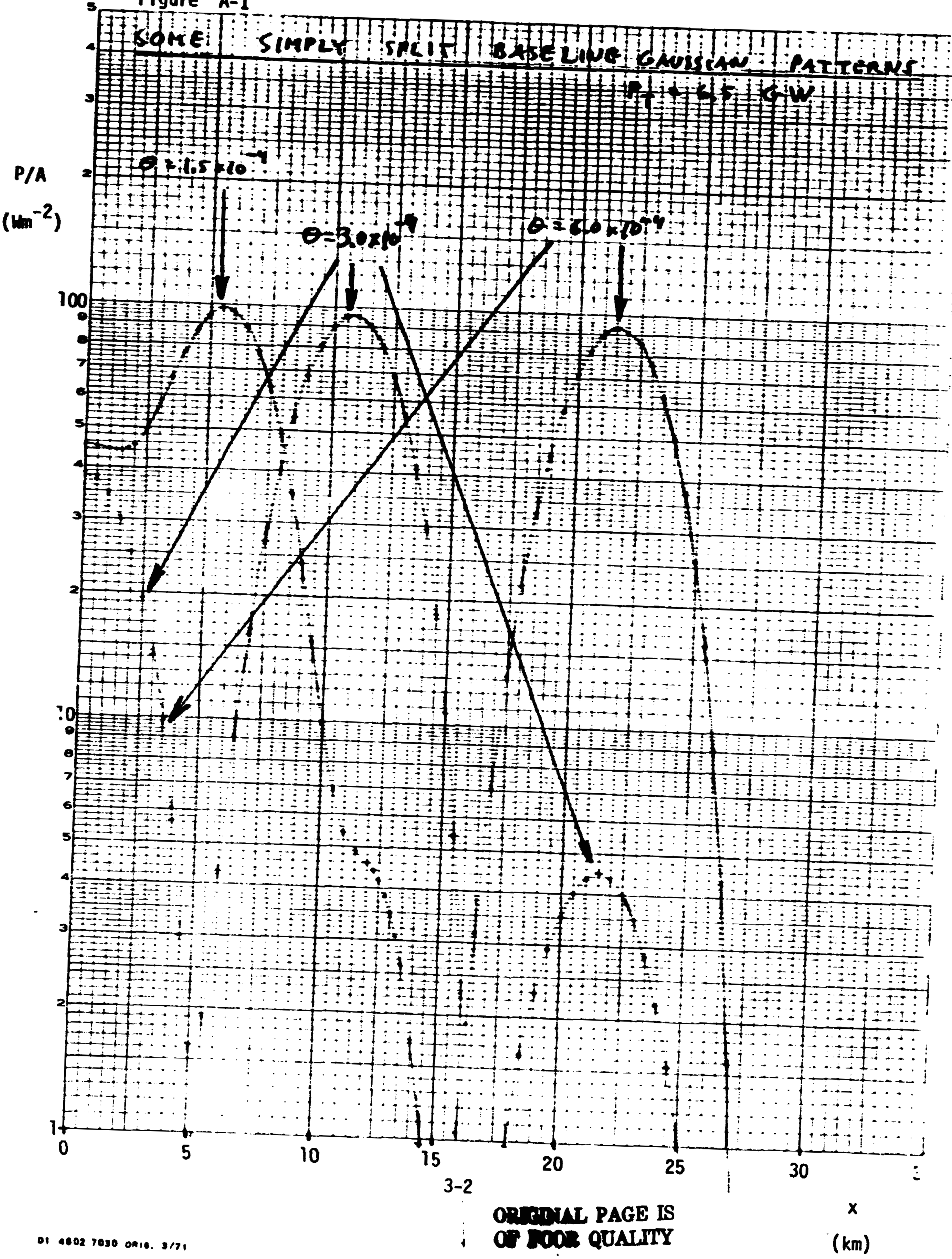
r = transmission distance

and θ = beam split angle

This is not necessarily a realistic modulation but was simple to implement and serves its function of demonstrating two beams well.

Results of a simply split 6.5 Gw baseline Gaussian are shown on Figure A-1, and are as predicted except for the central lobe which did not diminish as the split angle was increased to 6×10^{-4} radians. The central peak is somewhat of a mystery and may be due to an in-phase residual component in the spatial modulation or a grating lobe effect. Understanding and eliminating the central peak will be among our future efforts along with investigating various other multiple beam effects.

Figure A-1


SOME SIMPLY SPLIT BASELINE GAUSSIAN PATTERNS
$P_T = 6.5$ GW
$\theta = 1.5\times10^{-4}$
$\theta = 3.0\times10^{-4}$
$\theta = 6.0\times10^{-4}$
P/A
(Wm^{-2})
100
10
1
0
5
10
15
20
25
30
x
(km)

INITIAL MULTIPLE BEAM THEORY

I. BEAM FORMING

The linearity of electromagnetic fields is a well-known principle and allows the illumination of several spots from one aperture. The dimensions of the spots are all limited by diffraction and depend on the transmitting aperture dimensions, transmitting aperture power distribution and the desired power transmission efficiency. For a given configuration, the spot dimensions cannot be reduced without changing these parameters.

A way to think about this is to consider the transmitting aperture to be a screen across which a given field distribution may be defined. Define it to be like the field resulting from a sum of transmitting antennas behind the screen beaming through an opening in the screen towards their spots on the ground. (See Figure 1.) Alternatively, consider several apertures illuminating one screen and then apply reciprocity. In either case, synthesizing the beams boils down to duplicating the required field pattern across the screen.

In general the field pattern across the screen will be of uneven amplitude due to the addition and cancellation of phase fronts of different beams on the screen. I.E., there is a diffraction pattern which must reproduce in order to get beam separation. (See Figure 2.) For two beams of wavelength $\lambda = 12.24$ cm 2^{o} apart (i.e., about 1000 miles on the ground) there are nulls and peaks every 3.5 m. To implement this the least controllable unit of aperture area (i.e., the subarray) must be small compared to this, that is, probably on the order of 1 m on a side.

FIGURE I

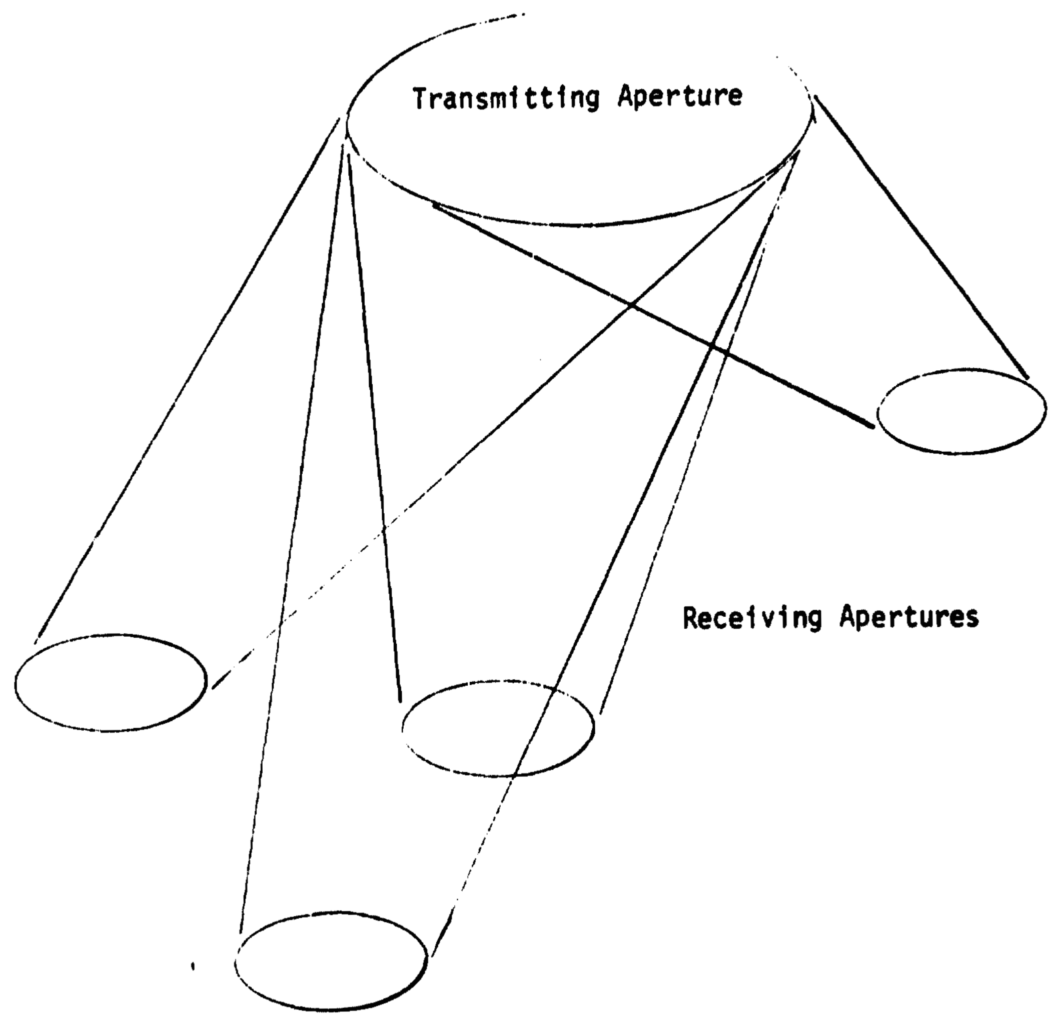
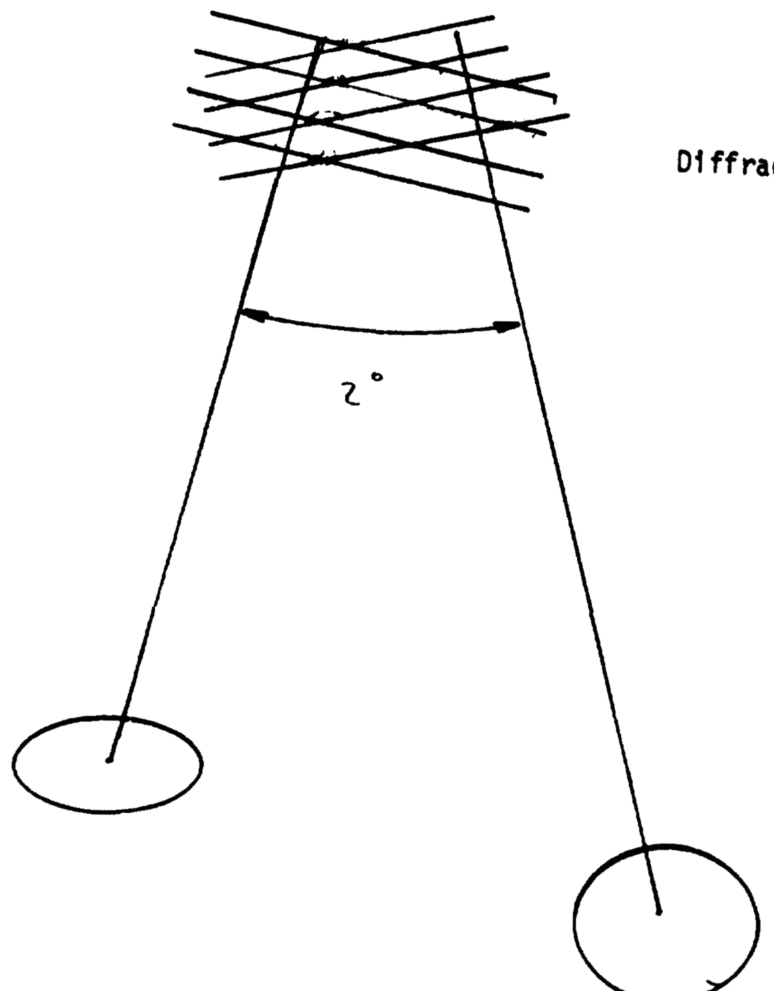


FIGURE 2



Diffraction Pattern:

$$R \sin \theta = \lambda$$

$$R = 3.5 \text{ m}$$

The required size of the least controllable units depends on the greatest angle between the beams more than anything else. Checking the capability of forming multiple beams via computer would be an instructive and useful thing to do here, as power satellite type arrays are not amenable to analytical calculations for any but simple cases.

Another thing that is immediately obvious when considering N beams over the transmitting aperture is that the peak RF power/area the subarrays must be capable of handling is N^2 the power/area due to a single beam and twice the mean power. This is an added expense, and may or may not be significant. It is probably possible to jitter the RF pattern across the transmitting aperture fast enough to beat thermal time constants, thereby avoiding derating the transmitting antenna average power. However, the components must still be able to stand the electrical stresses encountered at the power levels, and they must be able to be amplitude modulated at the jitter frequency.

An obvious question to ask is how the rectrodirective array concept is to be implemented for multiple beams. There seem to be several possible approaches.

Simplest is to use straight superposition of pilot beam signals at the same frequency. This requires no modification of the present system save n receiving arrays and a system to hold the n pilot beams close enough to each other in frequency to preclude rapid changes in the array patterns.

Another approach is to use slightly different frequencies for each pilot, receive and frequency convert the pilot signals separately,

amplify them to desired amplitudes and then combine the signals. This system is the same as the previous one in other respects. It does, however, have higher costs for receivers at the subarrays.

In either case, only a single reference phase distribution system for the transmitting array is necessary.

It may be desirable to hold the N pilot beams on the ground in phase with each other. The technology for doing this exists and is commonly used in radio astronomy.

A question that needs to be answered is how amplitude and phase errors introduced by the atmosphere on the uplink pilot beams and aboard the satellite by the electronics alter the transmitting array phasing and diffuse the beams.

II. SYSTEM SIZING CONSIDERATIONS

The two basic relations that size the SPS system are the far-field antenna relation

$$A_R\ A_T = G \tag{1}$$

and the energy conservation

$$(P/A)_T\ A_T = N\ (P/A)_R\ A_R \tag{2}$$

where

A_R = Receiving antenna area

A_T = Transmitting antenna area

G = a consistant, depending on desired ideal power transmission efficiency

$(P/A)_T$ = Power density averaged over the transmitting aperture

$(P/A)_R$ = Intercepted R.F. power density averaged over a single receiving aperture

N = Number of beams

For given transmitted and received aperture power distributions, $(P/A)_T$ is fixed by the peak RF power per unit area, which in turn is fixed by the DC-RF conversion efficiency and the available heat rejection capacity at the center of the transmitting array. Similarly, $(P/A)_R$ is fixed by the peak allowable RF power density at the receiving end of the system, fixed by the ionospheric limit, presently at 230 w m^{-2}.

Dividing both sides of (2) by $A_R^{-1}\ (P/A)_T$ gives

$$A_R\ A_T = G = N\ (P/A)_R (P/A)_T^{-1}\ A_R^2 \tag{3}$$

Solving for A_R gives

$$A_R = (G\ N^{-1}\ (P/A)_T\ (P/A)_R^{-1})^{\frac{1}{2}} \tag{4}$$

Since $A_T = G\ A_R^{-1}$

$$A_T = (G\ N\ (P/A)_T^{-1}\ (P/A)_R)^{\frac{1}{2}} \tag{5}$$

The power intercepted at a single receiver site is

$$\begin{aligned} P_R &= (P/A)_R\ A_R \\ &= (G\ N^{-1}\ (P/A)_T\ (P/A)_R)^{\frac{1}{2}} \end{aligned} \tag{6}$$

This yields a grid power of

$$P_G = P_R\ \eta_{RCV}$$

where

η_{RCV} = Receiver (Rectenna) efficiency

The transmitted RF power, P_T, is simply

$$\begin{aligned} P_T &= N\ P_R && = (P/A)_T\ A_T \\ &= (G\ N\ (P/A)_T(P/A)_R)^{\frac{1}{2}} && = (G\ N\ (P/A)_T\ (P/A)_R)^{\frac{1}{2}} \end{aligned} \tag{7}$$

and the rest of the satellite is sized accordingly.

In summary, the power and antenna size scaling relation for a solar power satellite transmitting multiple beams has been derived for cases where both arrays are constrained in such a way as to fix average RF power levels. For recently investigated solid state transmitting array satellites this is indeed the case.

It is also the case for systems with tube-type transmitting arrays because they also have finite maximum achievable RF power densities.

In this analysis no penalty was included for increased microwave power transmission system (MPTS) complexity due to smaller subarray size. Once we have a better understanding of the desired phase control system

and what it costs, it ought to be possible to include the subarray size into an analysis to trade subarray size for cost advantages due to multiple beam capability.

III. COST CONSIDERATIONS

This section contains a proof that cost of power from a multiple beam SPS system is the same as from a single beam system if there is no penalty introduced for control system complexity. Introduction of such penalties will, of course, favor single beams and multiple beams with small relative angles, if receiving cost per unit area is fixed.

A simple model for the cost of a power satellite is to consider the costs to be proportioned to solar-electric conversion system mass, aperture area mass and rectenna area. Denoting these costs to be C_{SE}, C_T and C_R, respectively, allows us to write down total cost C_1 for a single beam system:

$$C_1 = C_{SE} + C_T + C_R \tag{8}$$

For N beams this becomes

$$C_n = N^{\frac{1}{2}} C_{SE} + N^{\frac{1}{2}} C_T + N \left(N^{-\frac{1}{2}} C_R\right) \tag{9}$$

If, for a single beam system, received power is P_1 for an N beam system the power received, P_N, is

$$P_N = N^{\frac{1}{2}} p, \tag{10}$$

Finally, the cost per unit power is

$$C_N P_N^{-1} = C_1 P_1^{-1}, \text{ i.e., independent of } N \tag{11}$$

IV. BEAM SCAN EFFECTS

In the preceding sections it was assumed that there was negligible beam pattern degradation due to scanning away from aperture boresight. This section outlines scan effects.

The most obvious beam pattern effect of scan is beam spreading due the cosine loss in the projected aperture area. Since the sort of scan angle, θ, we are considering is small, $(\cos\theta)^{-1} \simeq 1$, and the effect is to first order negligible.

Another commonly known effect is the variation of sidelobe level with scan and the number of beams. This probably has to be checked empirically from aperture array programs as there seems to be no clean analytical theory which allows sidelobe level prediction for more than one beam. However, since single beams are superposed to generate multiple beams, it seems clear that the worst sidelobe effects on the power will be due to the addition of the sidelobes between adjacent beams (See Figure 3.)

A final effect of scanning to create multiple beams is quantization error due to the fact that each subarray represents a patch of constant amplitude and phase. If one can assume the errors are essentially random, Ruze[1] and Schanda[2] have shown that phase errors contribute the most to beam pattern degradation in the fashion $G = G_0 e^{-\overline{E^2}}$

where

G = Main beam gain

G_0 = Main beam gain without phase errors

$\overline{E^2}$ = Mean square phase error

Note that the fraction

$$1 - e^{-\overline{\varepsilon^2}}$$

represents a loss in efficiency that can't be recovered, and thus should be kept small.

V. CONCLUSIONS

Going to multiple beams requires greater spatial resolution at the transmitting aperture. The resolution required goes as the angle between the most widely separated beams, and will be on the order of 1 m.

For the case of ionospheric beam power limitation at the receivers and RF power density limits at the transmitter, space system design areas and powers scale as $N^{1/2}$, whereas the same parameters on the ground go as $N^{-1/2}$.

To first approximation cost of power is invariant of the number of beams.

A final comment: The small subarray size might be considered to be incompatible with current SPS designs, but this is not necessarily so. The ongoing solid state SPS antenna design breaks up the transmitting area into many small radiating units smaller than λ on a side. Putting them in groups of 200 to 400 to make a 1 m subarray seems to pose no greater fundamental problems than combining them into larger groups and trying to keep them in phase.

VI. REFERENCES

1) Ruze, J., IEEE Proceedings 54, #4, "Antenna Tolerance Theory - A Review," pp. 633-644 (April 1966).

2) Schanda, E., IEEE Trans. on Antennas and Propagation, AP - 15, pp. 471-473 (May 1967)

TASK 42121, 42122, AND 42124
GEO CONSTRUCTION BASE DESIGN AND ANALYSIS

CONTENTS

CONTENTS (contd)

ILLUSTRATIONS

ILLUSTRATIONS (contd)

ILLUSTRATIONS (contd)

ILLUSTRATIONS (contd)

TABLES

TASK 42121, 42122, AND 42124
GEO CONSTRUCTION BASE DESIGN AND ANALYSIS

1 - INTRODUCTION

Grumman's Phase 2 effort was focused on further defining the operations and systems of the 4 Bay End Builder Construction Base. This section describes the work performed in updating the GEO Base system configuration, updating the crew module definition and defining a concept for GEO Base buildup. Related analysis on SPS construction operations, base operations and base cargo handling and distribution operations are provided in the Phase 2 SPS Operations and Systems Synthesis Report, Volume III, Section 12.

Grumman's 4 Bay End Builder concept was developed in Phase 1 and evaluated against alternate satellite construction concepts, as illustrated in Figure 1. The single pass 8 bay wide end builder concept was found to exhibit the highest cost and be underutilized, if only one satellite is built every six months. The comparison of multi pass end builders and the single deck platform concepts was nearly even with respect to cost, mass and risk. The 4 Bay End Builder was selected, however, for further work in Phase 2 due to its greater production rate growth capability. The updated configuration of the 4 Bay End Builder is shown in Figure 2.

The 4 Bay End Builder Construction Base assembles the 5 GW reference Solar Power Satellite entirely in geosynchronous orbit, as illustrated in Figure 3. The 8 bay wide satellite energy conversion system is constructed in two successive passes on one side of the base, while the microwave antenna is assembled on the other side of the base. On the first construction pass, the GEO base builds one-half of the energy conversion system, a 4 bay wide strip by 16 bays long. When this part of the satellite has been constructed, the base is indexed back along the edge of the structure to the first end frame. During the second construction pass, the 4 bay wide strip is attached directly to the assembled satellite systems. At the end of the second pass, the base is then indexed sideward to mate the antenna with the center line of the energy conversion system. After final test and check out, the base separates from the satellite and is transferred to the next orbital position for SPS construction.

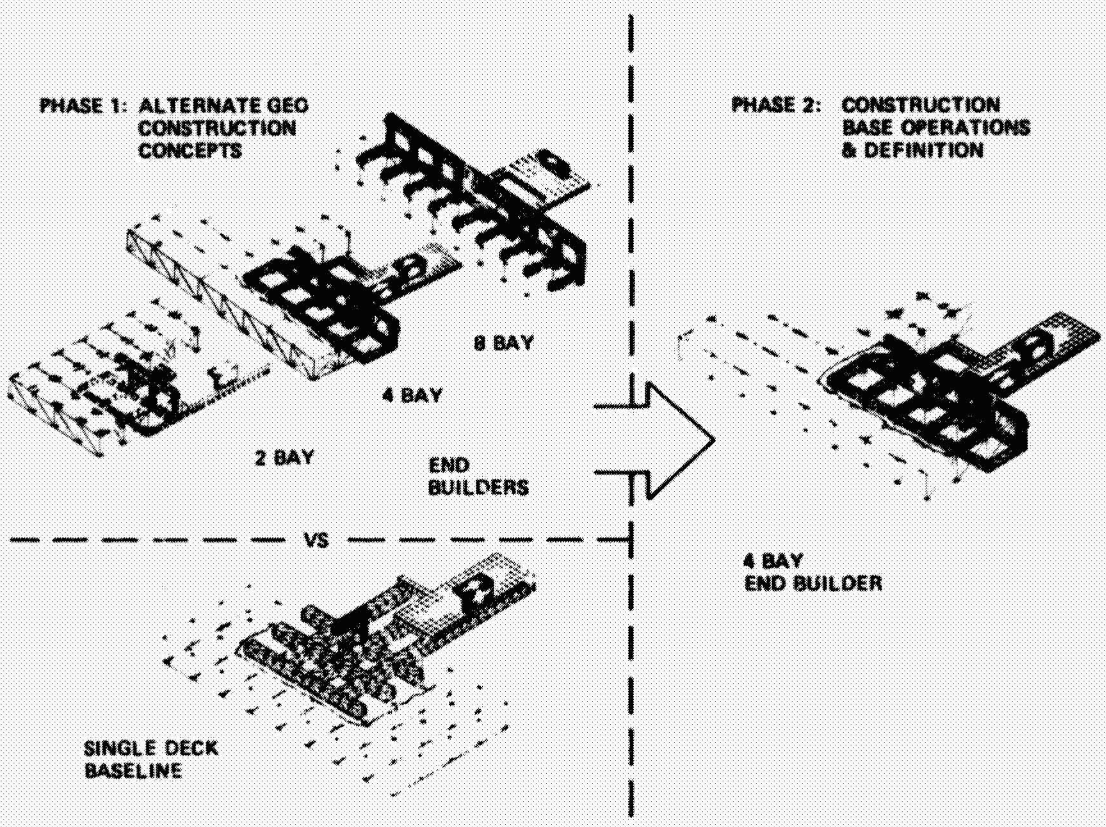


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Figure 1 SPS System Definition Study for Boeing/JSC

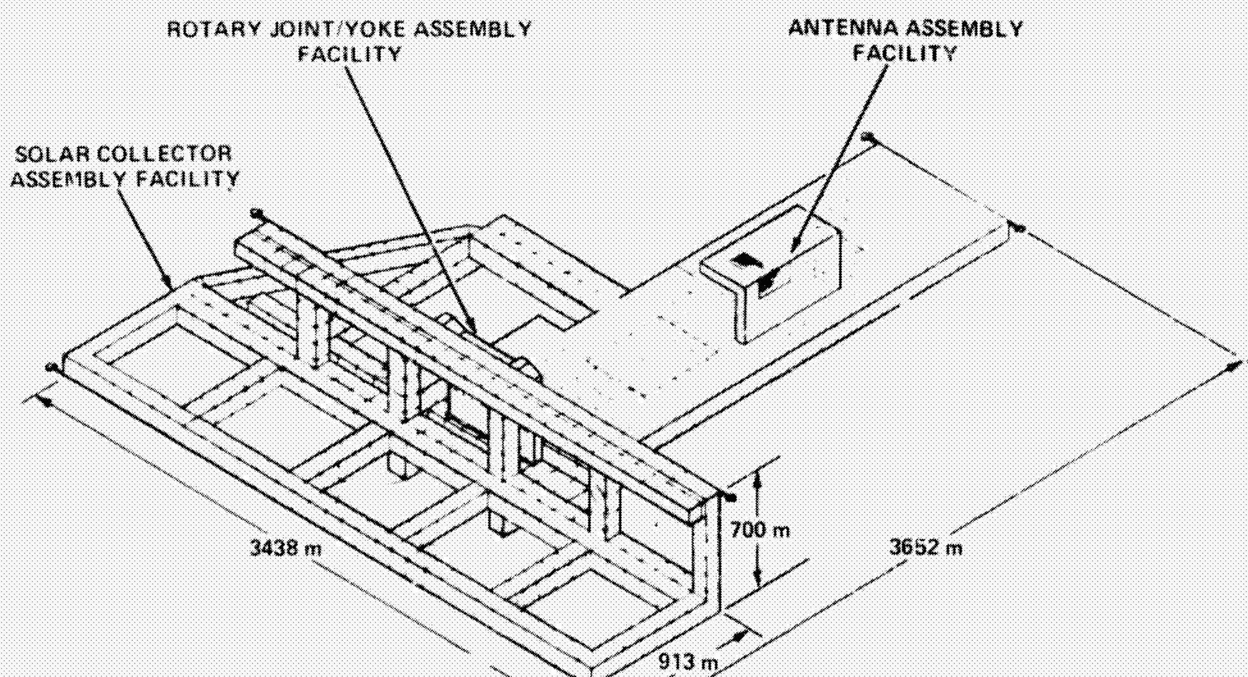

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Figure 2 4 Bay End Builder Construction Base - Update

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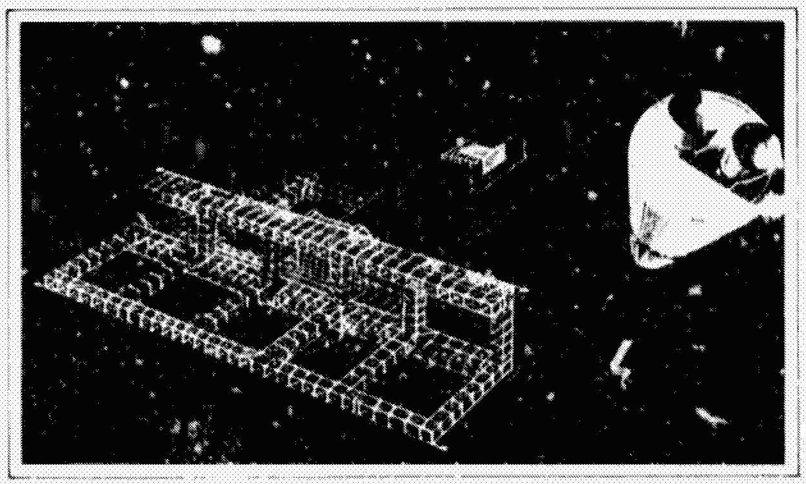
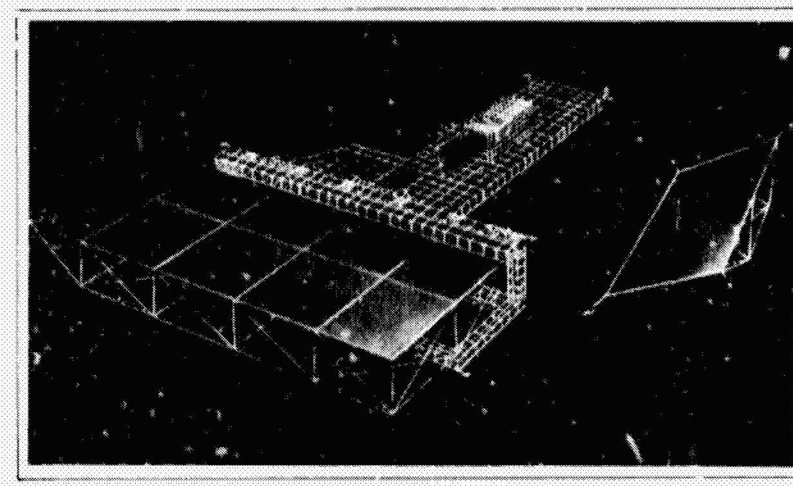
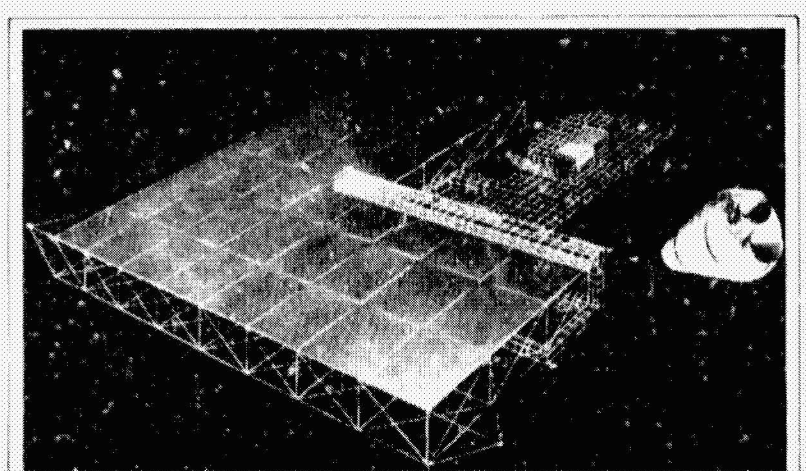


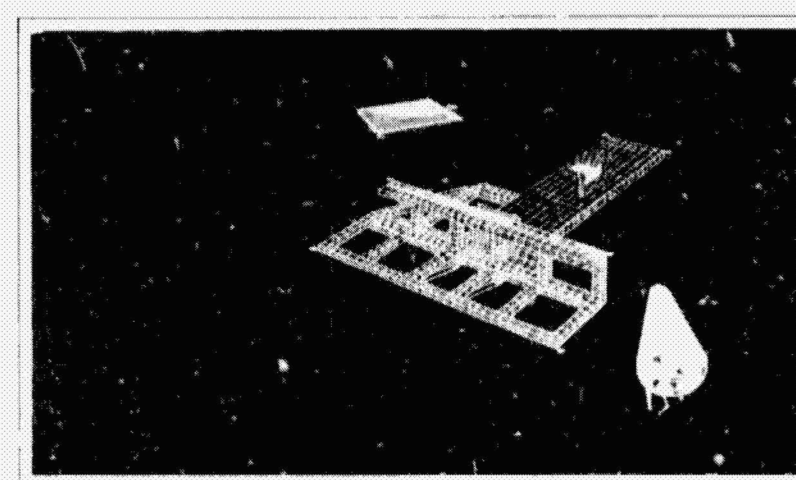
ACTIVATE GEO BASE



FIRST CONSTRUCTION PASS



SECOND CONSTRUCTION PASS



CHECKOUT SPS & TRANSFER BASE

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Figure 3 SPS — 4 End Builder Construction

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2 GEO BASE CONFIGURATION UPDATE

The Solar Power Satellite GEO Construction Base is required to assemble one 5GW reference satellite every six months or two satellites per year for 30 years. As in Phase 1, free flying construction facilities and/or assembly methods are to be avoided in further refinement of the 4 Bay End Builder concept. Therefore, the base is also required to provide contiguous facilities for assembling all SPS system elements. As a GEO operational base, the 4 Bay End Builder must be capable of docking and unloading orbital transport vehicles and implementing other essential work support and crew support functions as well. The top level requirements that established the design and operations of the SPS GEO base are shown in Figure 4. These requirements are extracted from the Phase 1 study and guide the definition of all other requirements. For example, essential base operational areas include: command and control modules, crew habitats, cargo handling and distribution network, subassembly factories, base attitude control, base electrical power, base maintenance, etc. The GEO base is also required to service orbital transfer vehicles and support the operational maintenance of commissioned satellites.

Hence, in addition to building the SPS, the GEO base must fulfill strenuous logistic support requirements, as shown in Figure 5.

Every thirteen days an EOTV will arrive with large Cargo Pallets. A dedicated area must be available at the GEO Base to transfer this material on board in a quick and efficient manner. At the same time, empty pallets have to be removed from the base. As soon as the Cargo Pallets are landed, they have to be moved to an unloading/ sorting area and processed through the construction base. To accomplish this, an efficient transport system must be available. Level J, the top deck of the base shown in Figure 6, provides 6.1 Km of main line track and 5.1 Km of connecting spur lines.

The base has to rotate the 444 man crew at planned intervals. When satellite maintenance support operations are included the total crew complement will increase in proportion to the size of the operational fleet and the maintenance schedule adopted. Assuming that scheduled maintenance is performed twice a year on a 20 to 60 SPS fleet, then an additional 383 to 1149 personnel must also be accommodated. All these people

- CONSTRUCT ONE 5 GW SPS WITHIN 6 MONTHS ·5%
- ENERGY CONVERSION & MICROWAVE POWER CONSTRUCTION FACILITIES CONTIGUOUS
- CONSTRUCTION APPROACH:
  - ENERGY CONVERSION – TWO PASS LONGITUDINAL BUILDUP
  - MICROWAVE POWER – ELEVEN ROW LATERAL BUILDUP
- DESIGN LIFE: 30 + YEARS
- DOCKING & OFFLOADING SYSTEM FOR POTV, CARGO TUG & OTV
- OPERATIONAL AREAS FOR: COMMAND & CONTROL MODULES, CARGO WAREHOUSING, SUBASSEMBLY FACTORIES, CREW & WORK MODULES, BASE MAINTENANCE, OTV MAINTENANCE, EOTV MAINTENANCE, OPERATIONAL SPS MAINTENANCE & TRAINING
- BASE LOGISTIC VEHICLES & TRACK NETWORK
- CONSTRUCTION ACCURACY & QUALITY
- BASE ATTITUDE CONTROL, STATIONKEEPING, LONGITUDINAL TRANSFER CAPABILITY
- BASE ELECTRICAL POWER, COMMUNICATION & DATA MANAGEMENT CAPABILITIES

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Figure 4 GEO Base System Requirements

- EOTV CARGO DELIVERY
  - 4000 MT UP & 200 MT DOWN/FLIGHT · EVERY 13 DAYS
  - OPERATE & SERVICE 2 CARGO TRANSFER TUGS
  - DOCK & UNLOAD 10 TO 20 CARGO PALLETS
  - PROVIDE PALLET TRANSPORTERS
- POTV GEO CREW ROTATION
  - ROTATE UP TO 75-80 PEOPLE/FLIGHT @ 15-DAY INTERVALS
  - MAINTAIN TRANSIENT CREW QUARTERS
  - DOCK 4 POTVs & PROVIDE INTRA-BASE CREW BUSES
- SPS OPERATIONAL MAINTENANCE SUPPORT (PER 20 SATELLITES)
  - LOAD/UNLOAD SPS COMPONENT RACKS @ 4½-DAY INTERVALS
  - MAINTAIN RECONDITIONED & DEFECTIVE COMPONENT STORAGE
  - DOCK & SERVICE SPS MAINT FLEET (4 OTVs & 4 PAYLOADS) MAINTAIN KTM/COMPONENT REFURB FACILITIES
  - PROVIDE CREW HABITATS

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Figure 5 GEO Base Logistic Support Requirements

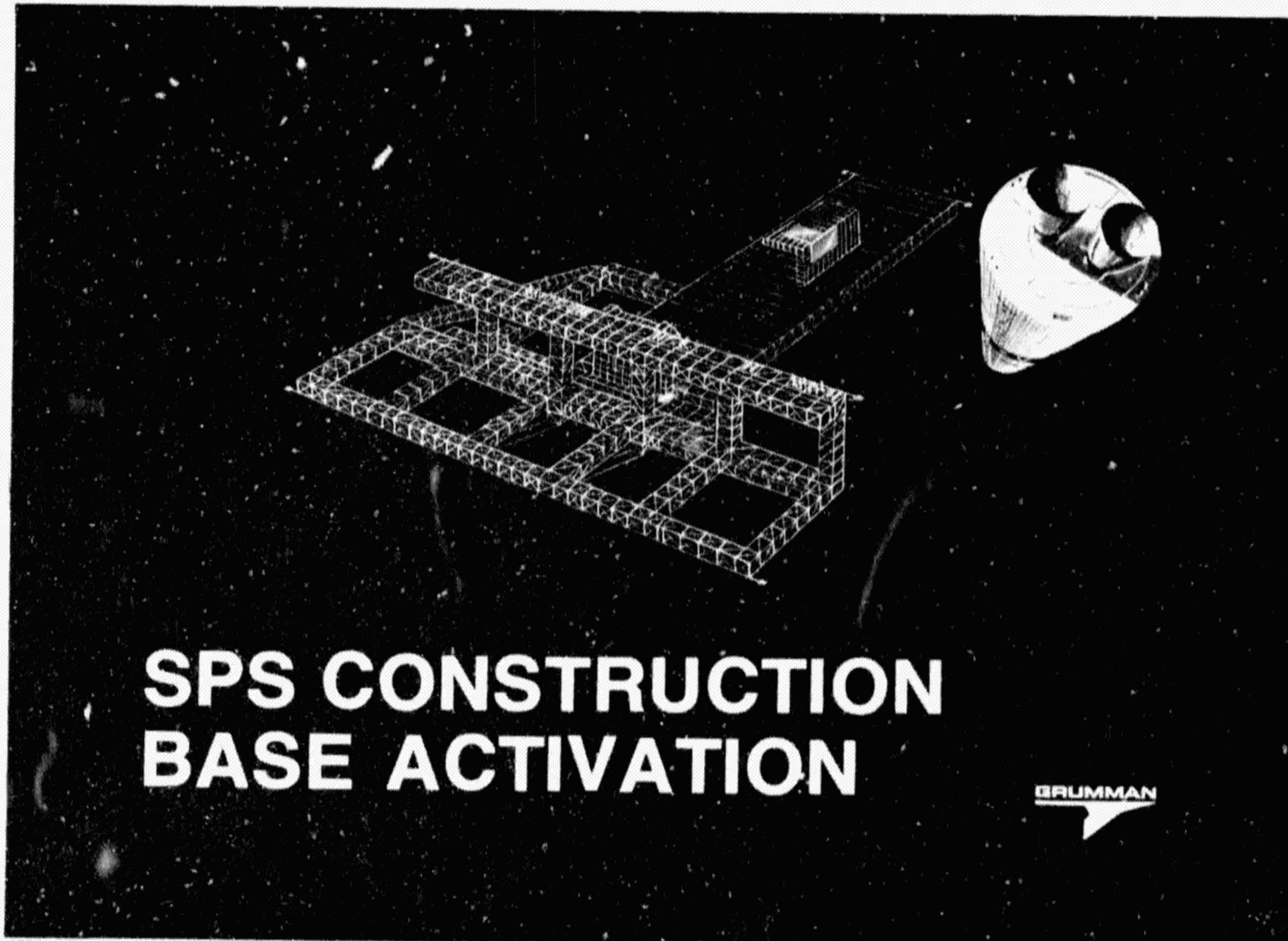

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Figure 6 SPS Construction Base Activation

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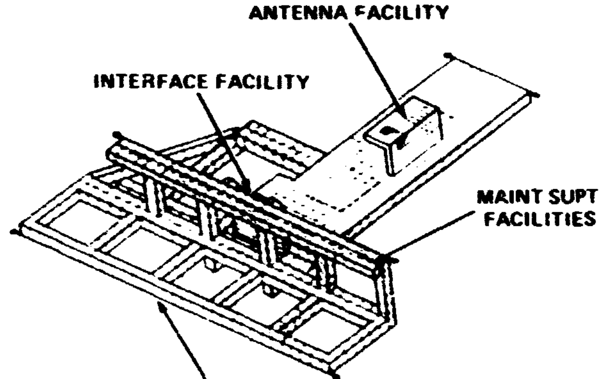
have to be housed comfortably and transported to their assigned work stations each day. Each time a new crew is brought up, resupplies must also be provided.

The other function of the base is to serve as a home base for service of all outlying SPS stations. Defective material on the SPSs must be replaced, brought back to the base and reconditioned. The refurbished material is stored until needed as replacement parts on the next visit to the SPS stations.

Updated mass and cost estimates for the GEO Construction Base are provided in Figure 7.



- TWO 5GW SPS ASSEMBLED & C/O PER YEAR
- BASE CONSTRUCTION FACILITIES
  - UNIT COST (1979 $) $ 8.48 B
  - MASS 6390 MT
  - TOTAL CREW 444
- ADD-ON MAINT. SUPT. FACILITIES
  - COST DELTA $ 3.21 to $9.63 B
  - ADD'L MASS 1326 TO 3979 MT
  - ADD'L CREW 383 TO 1149

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Figure 7 4-Bay End Builder GEO Base Features

2.1 CONSTRUCTION FACILITIES & EQUIPMENT

The GEO base has contiguous facilities for concurrent assembly and subsequent mating of the satellite energy conversion system and its power transmission antenna. To implement these construction operations, the base structure serves as an assembly jig which also supports the construction equipment, cargo handling and distribution system, subassembly factories, test and checkout facilities, transportation vehicle maintenance and base subsystems. When SPS Power Transmission Operations begin, the GEO base will also support SPS maintenance facilities. Crew support facilities are included on the GEO base.

The overall base shown in Figure 8. is 3.44 Km wide x 3.65 Km long x 0.9 Km deep with eleven levels of the energy conversion and antenna construction facilities identified with letters A through L, as shown in Figure 9. The elevations are taken from the base level A of the factory reference line (FRL) and are given in meters.

The major construction facilities of the GEO base are tailored to the structural cross section and support requirements for assembling their respective SPS systems. The solar collector assembly facility is designed to provide a fully assembled 8x16 bay reference system after two 4 bay wide longitudinal construction passes. The antenna assembly facility, which may be seen in Figure 10. is arranged for progressive build-up of the microwave antenna, i.e. assembling one row at a time until the 11 row planform is fully constructed.

2.1.1 Solar Collector & Antenna Assembly Facilities

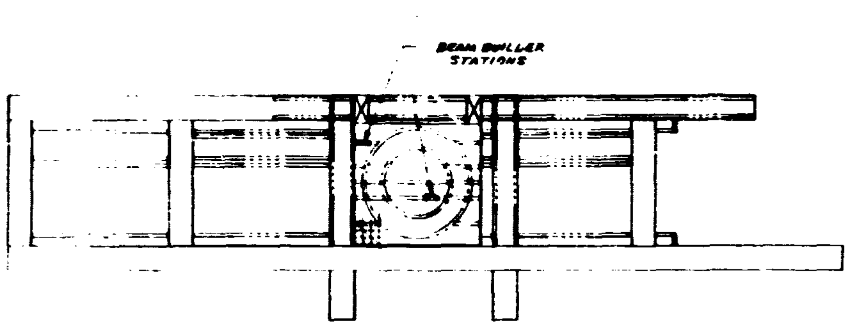
The SPS energy conversion system is assembled during 2 successive passes by the L-shaped framework shown in Figure 11. The GEO base structure supports the emerging satellite during all phases of construction.

The width of this framework (3.44 km) encompasses a 5 bay segment of the energy conversion structure to provide a one bay overlap for lateral and longitudinal indexing operations, as shown in Figure 12. The 700 m high open truss is sufficient to house beam fabrication stations, solar blanket installation equipment, bus installation mechanisms, crew facilities, docking, storage, intra base transport, etc. The other leg of the facility (913 m long) guides and supports the satellite until all systems are mated and checked out. The antenna assembly platform, which is located at the rear of the base, is arranged to facilitate the construction and attachment of the antenna and rotary joint interface. This open truss platform (2.51 km x 0.83 km) also supports the antenna/yoke assembly during the lateral index and mating operations with the assembled 8 x 16 bay energy conversion system. The framework provided for the yoke/rotary joint assembly facility and antenna assembly facility is sufficient to house the required construction equipment.

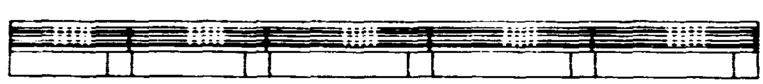
The primary structure of the GEO base is nominally assembled with a 100 m square framework, which includes diagonal shear members on each face. The small assembly facilities, which are used to build the yoke and antenna, are assembled with a 50 m lattice. All structural members used in these frameworks are fabricated by automatic beam machines developed to build the operational SPS. It is assumed that both 7.5m and 12.7m triangular section, closed-chord composite beams are used. Ground fabricated fittings and deployable members are also expected to be used on the base structure.

- Solar Collector Assembly/Fabrication - The end builder construction system, shown in Figure 13, is tailored to the structural cross section of the satellite and uses ten (10) dedicated semi-fixed beam machines to automatically fabricate continuous longitudinal members. Lateral and diagonal members of the structural assembly are fabricated by three (3) mobile beam machines. The assembly sequence as illustrated begins with Step 1, the assembly of the first frame and its attachment to the longitudinal members. The structural members of the frame are fabricated by three mobile beam machines that travel from one position to the next. The upper lateral beam is fabricated and then positioned for assembly. As this member is being joined, the mobile beam machines fabricate the other members of the frame needed to complete the assembly. Step 2 indexes the frame for one bay length by fabricating the continuous longitudinal beams from the dedicated beam machines. In Step 3, the next frame is built as in Step 1. During these three steps, power busses and solar array blankets are installed in parallel. The solar array blankets are deployed in the direction of build, are attached to the upper lateral beams and are fed out of cannisters, as the structure indexes. Longitudinal busses are installed "on the fly" as the structure is indexed; lateral busses are installed before a bay is indexed. In Step 4 the bay structure diagonal beams are fabricated and assembled to complete the bay. Figure 14 identifies the assembly equipment and construction sequence required to assemble the structural bays of the energy conversion module. The first bay of the four-bay pass is shown requiring the use of longitudinal beam machines (semi-fixed), three (3) mobile beam machines and four (4) cherrypickers. The operating paths of the mobile beam machine and cherrypickers are also defined along with the fabricating sequence of each of the mobile beam machines. This sequence is then repeated for bays 2, 3 and 4. This row is then indexed, as in Step 2, and the entire sequence repeated until the energy conversion structure is built.

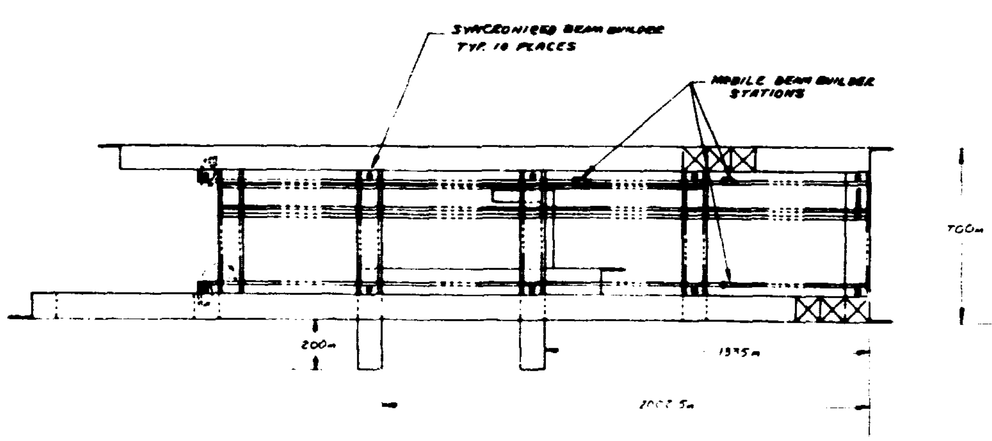
- SPS Energy Conversion Assembly Operations - Figure 15 depicts the construction activities at levels F, G, and H of the energy conversion construction facility. These levels are utilized in the construction of the upper surface of the energy conversion module. Shown nestled in the facility structure is the 7.5 m longitudinal beam machine (semi-fixed), and operating from a horizontally mounted track system are two mobile beam machines. One beam machine is shown fabricating the 7.5 m bracing beam and the other, a 12.7 m lateral

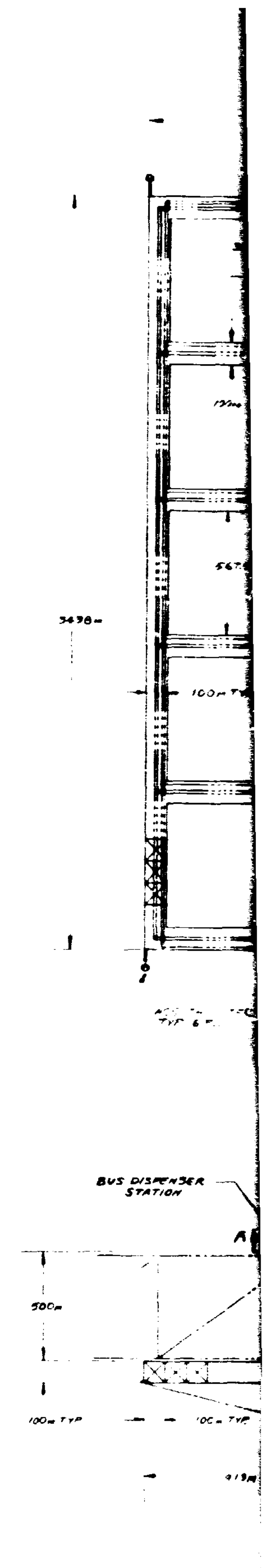


SECTION B-B



SECTION A-A





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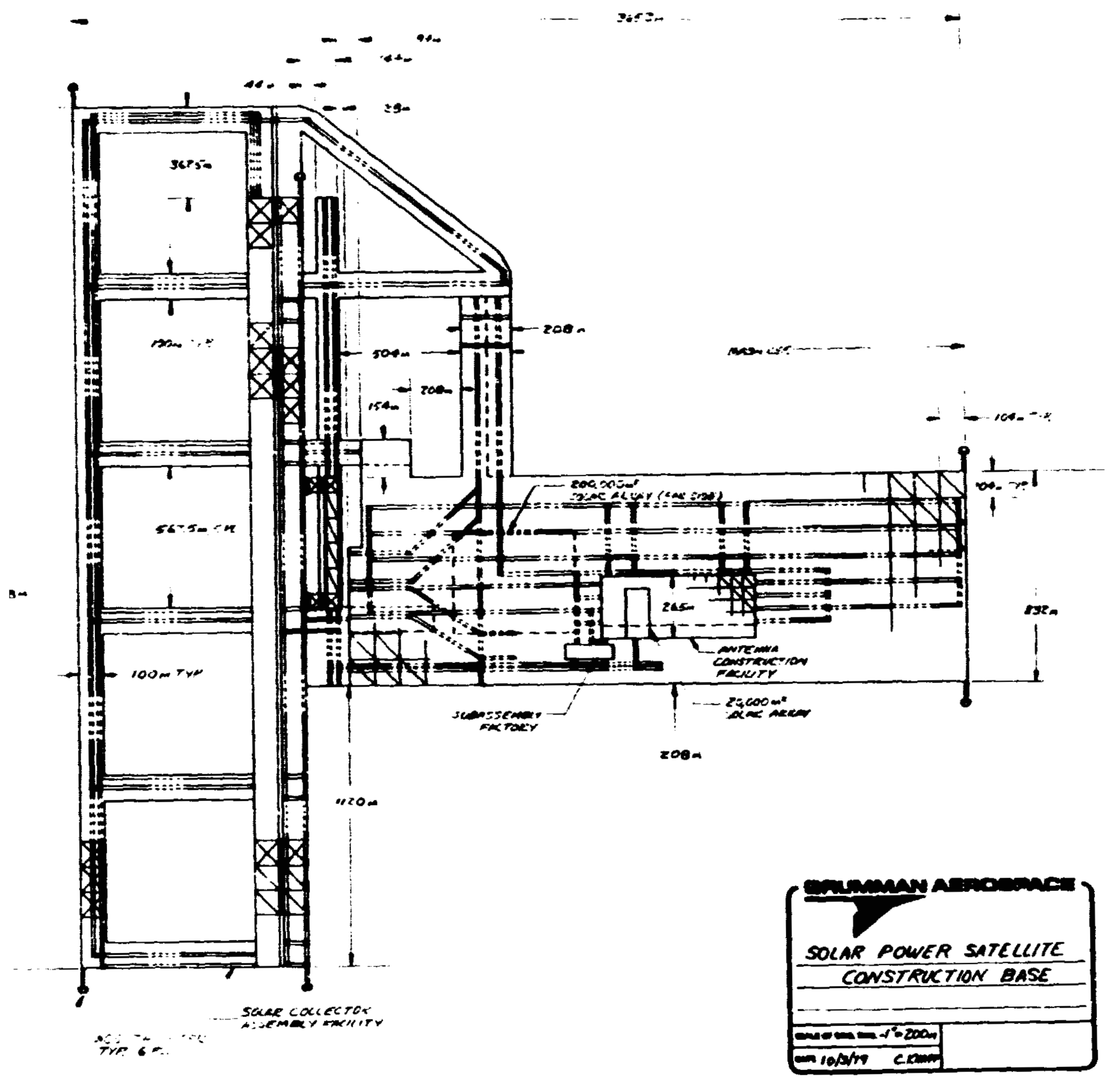

FOLDOUT FRAME 2

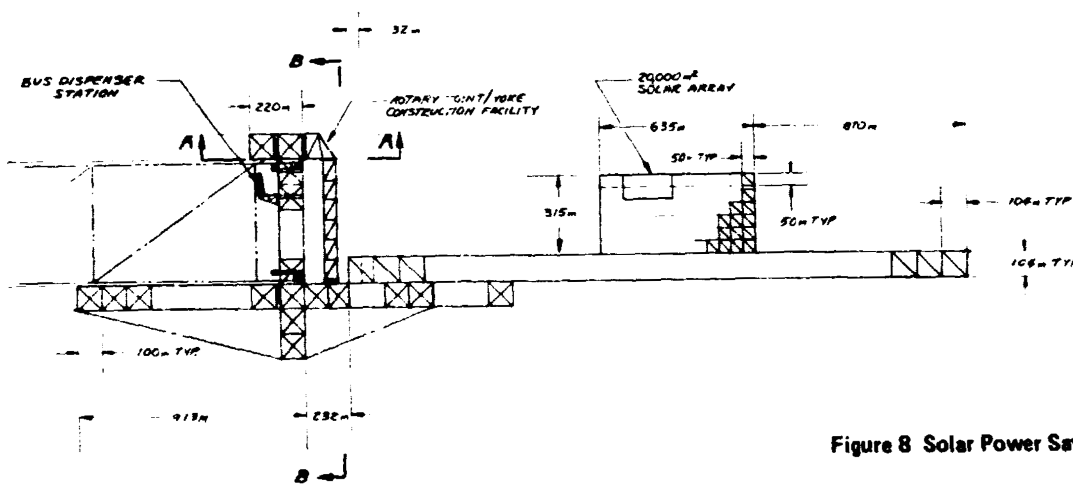

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Figure 8 Solar Power Satellite Construction Base

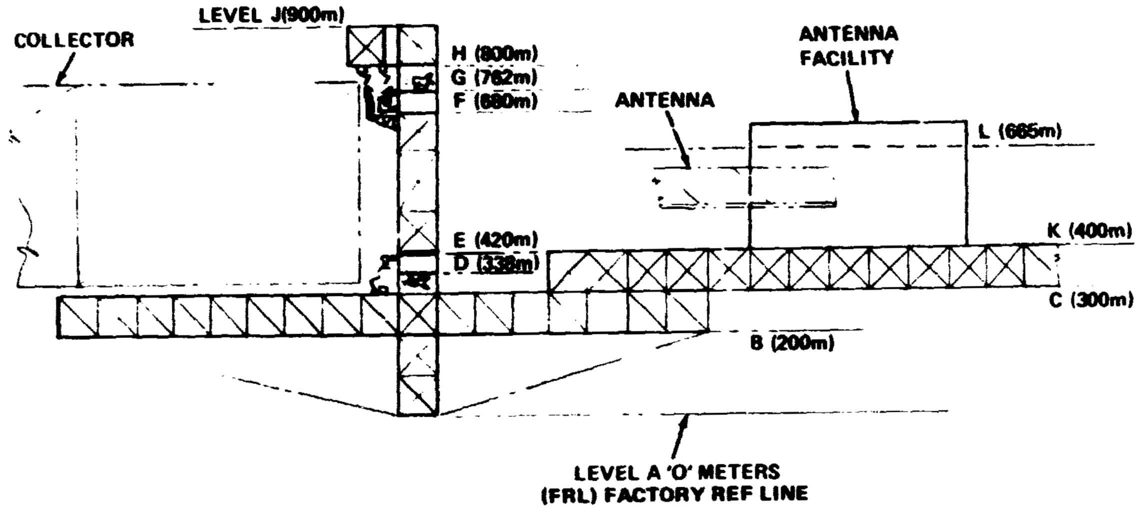

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Figure 9 GEO Factory Level Identification — Baseline

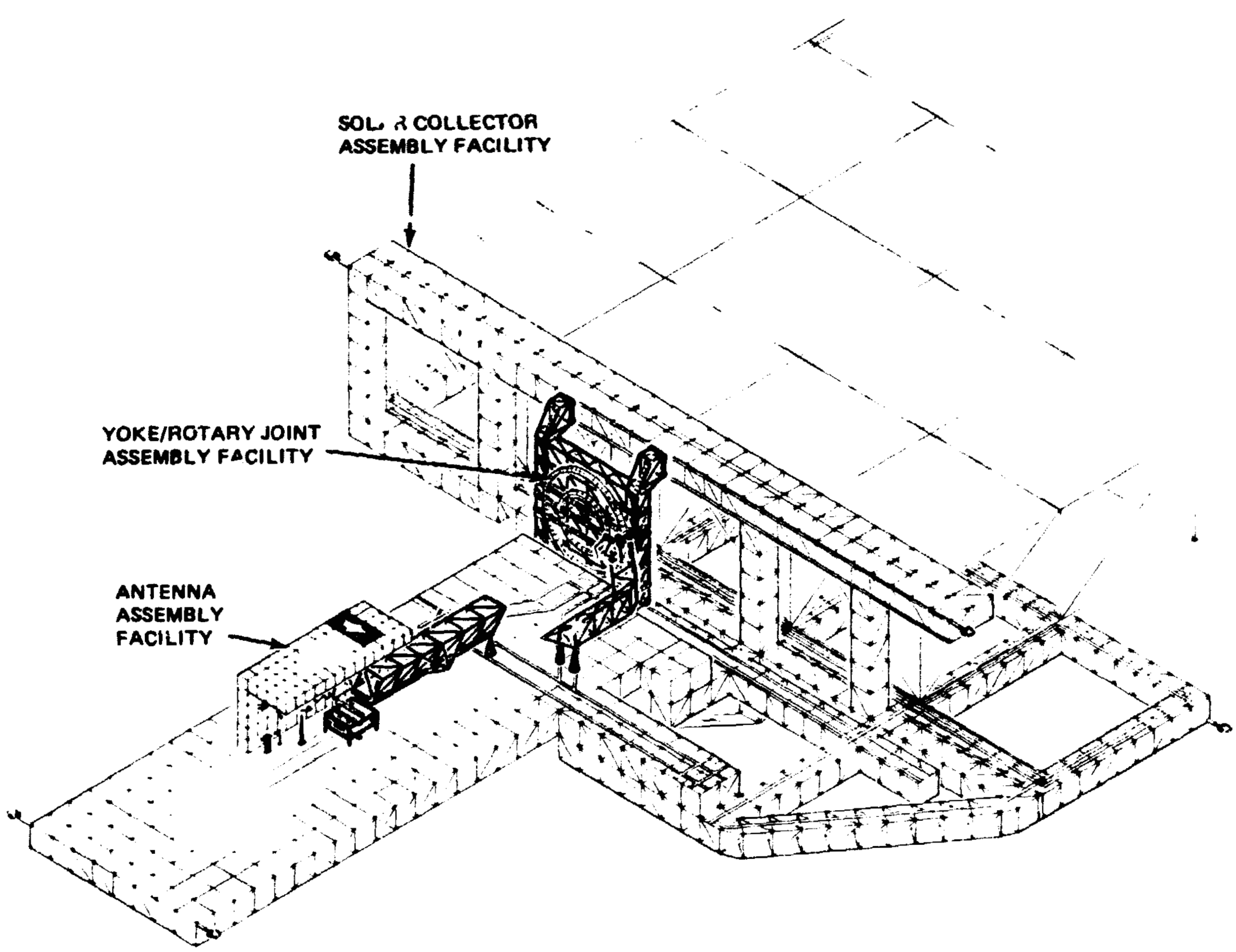

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Figure 10 4-Bay End Builder - Initial Construction

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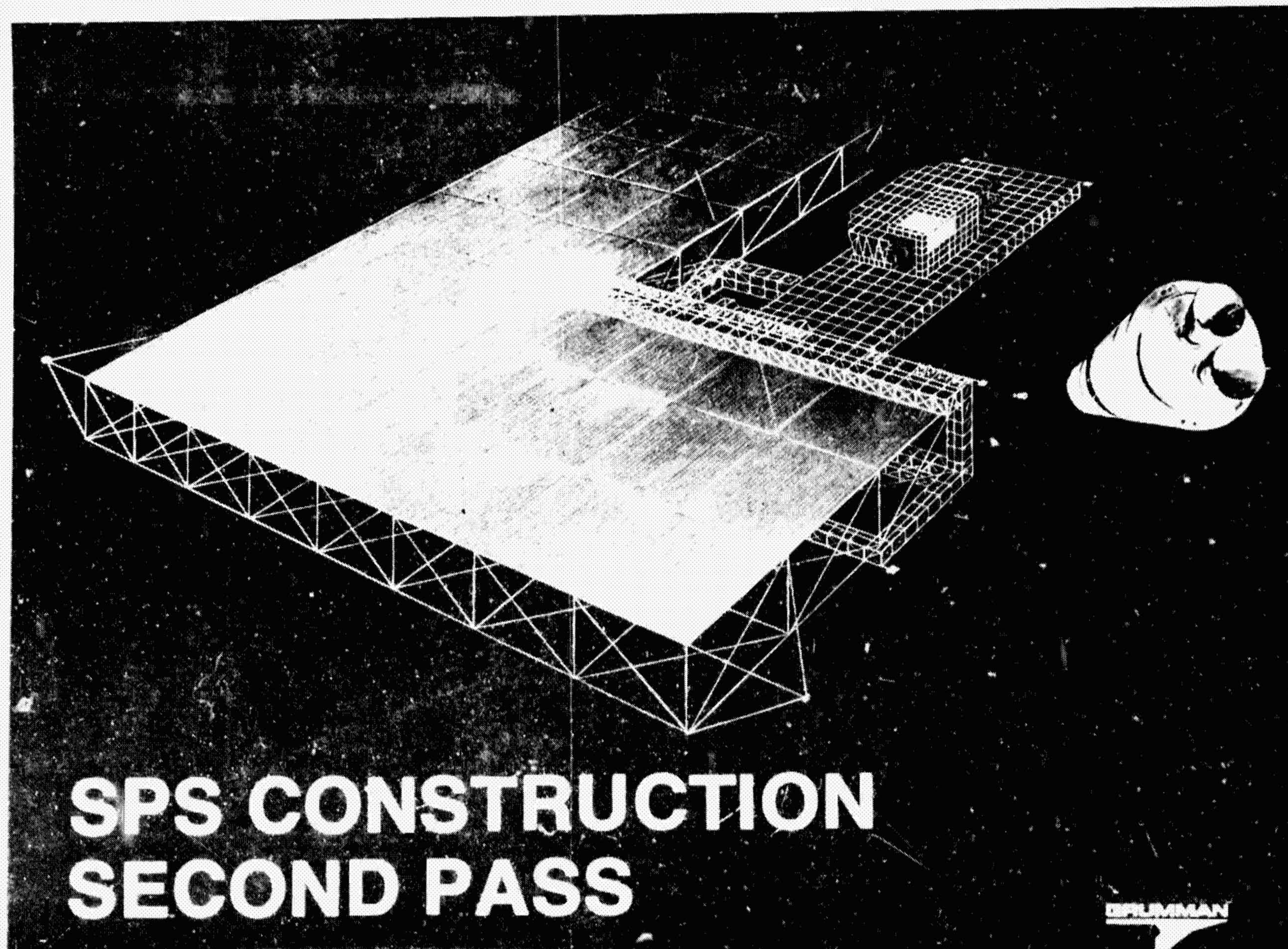

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Figure 11 SPS Construction Second Pass

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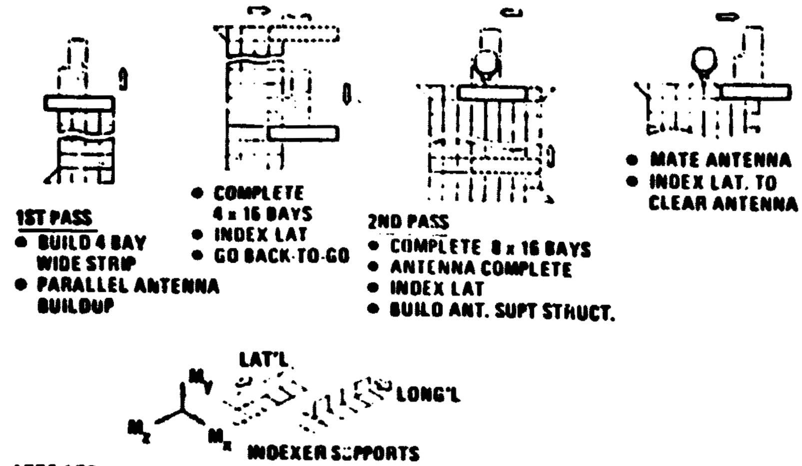

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Figure 12 4 Bay End Builder Construction Sequence

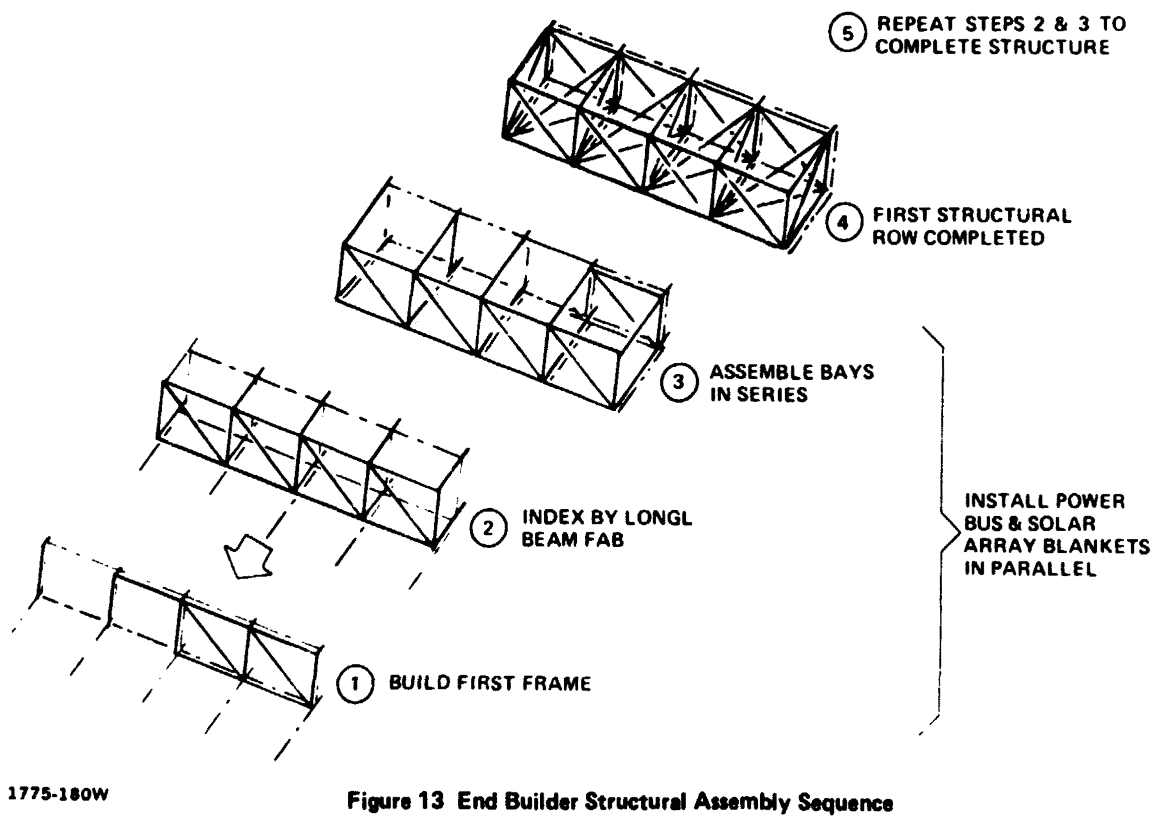

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Figure 13 End Builder Structural Assembly Sequence

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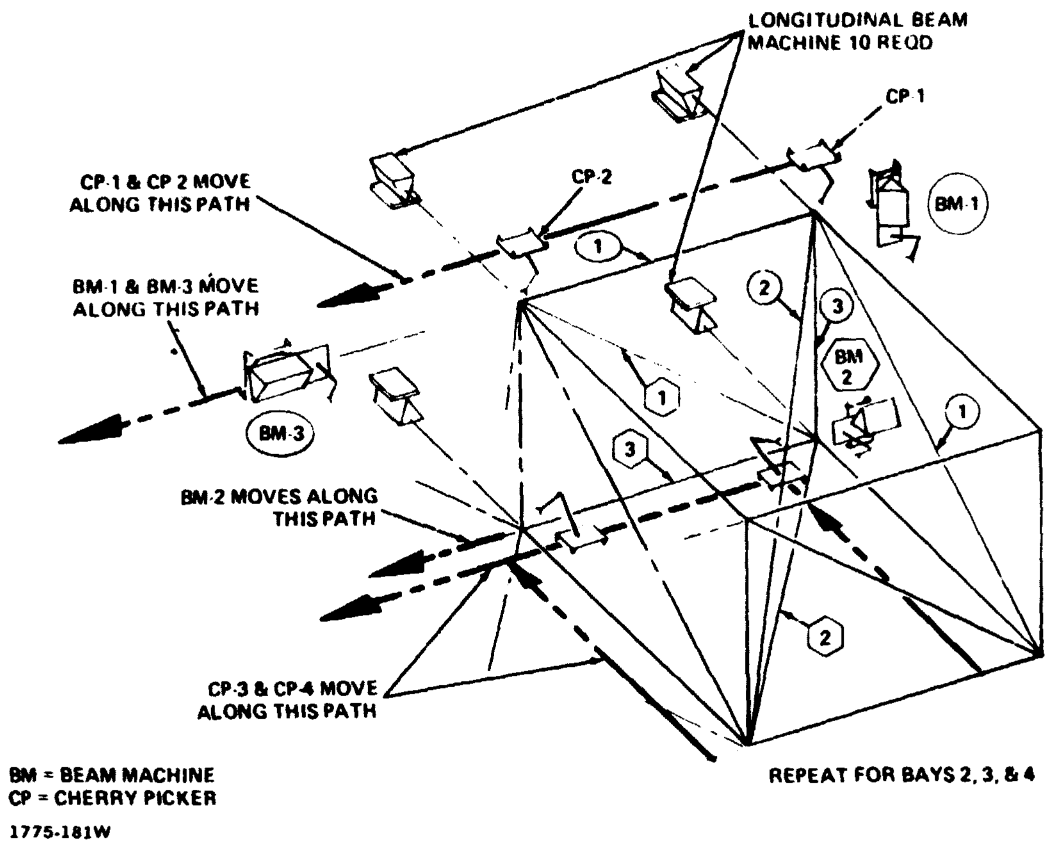

Figure 14 Energy Conversion Structure — Assembly Equipment & Sequence — 1st Bay

(solar array support) beam. Located overhead on the facility overhang and operating from a track system, cherrypickers are used to maneuver and attach the completed beams. The complex operations of these two cherrypickers in the maneuvering, handing-off and installation of beam lengths of approximately 600 to 1000 meters requires further study.

Solar array blanket deployment and installation is coupled with the end builder structural assembly sequence. Shown are the blanket installers operating from a track system mounted on the facility overhang. The solar array blankets are deployed from canisters mounted on the overhang. Replacement canisters are shown being moved into place and installed at their deployment station by a mobile flatbed cherrypicker.

The arrangement of major construction equipment at levels F, G, and H is also shown in Figure 16. The level G 7.5 m longitudinal beam builder substation is provided with 60 m travel distance to permit on-line maintenance and repair for continuity of construction operations. This provides about 1 hour for the repair

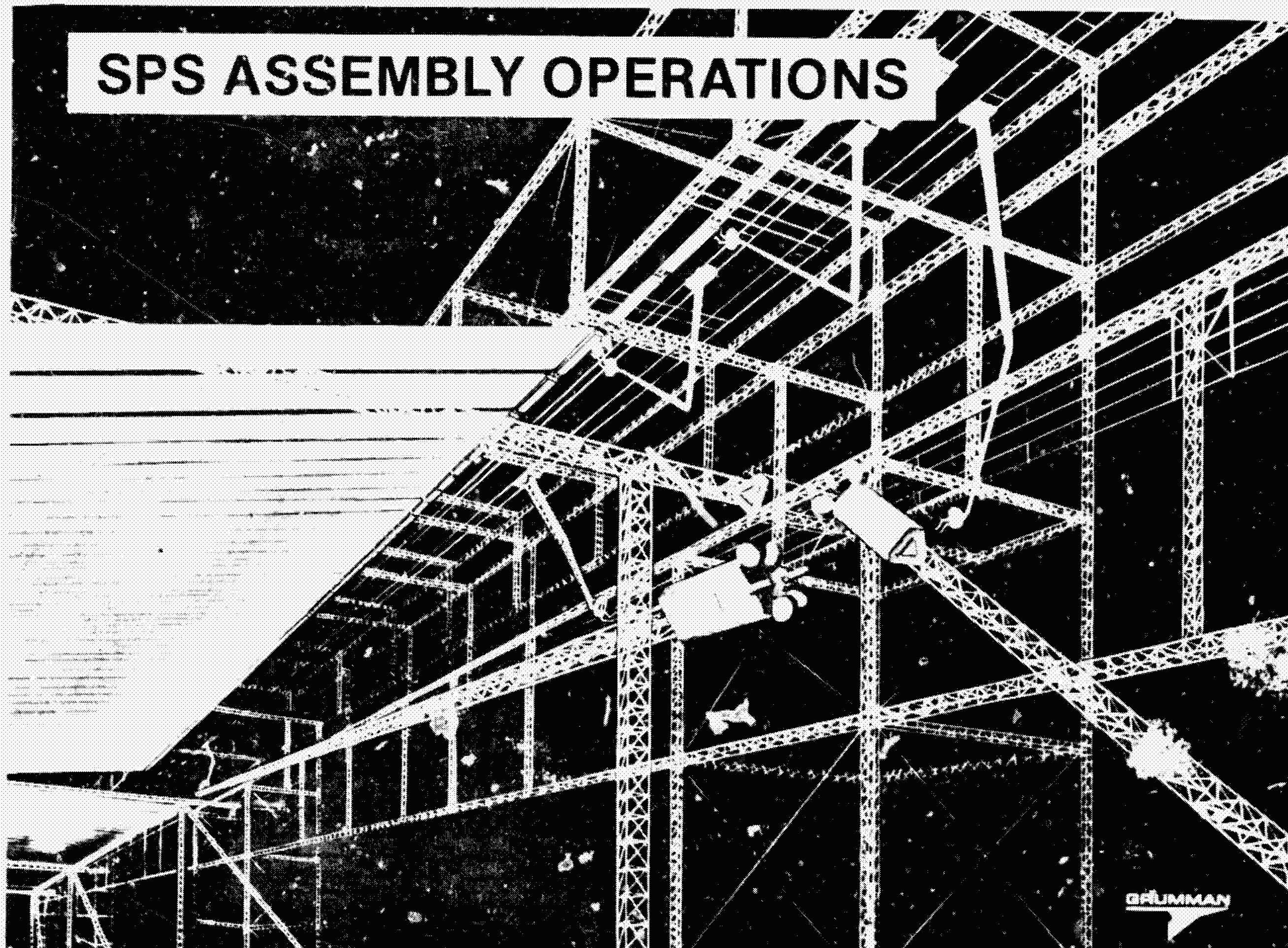

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Figure 15 SPS Assembly Operations

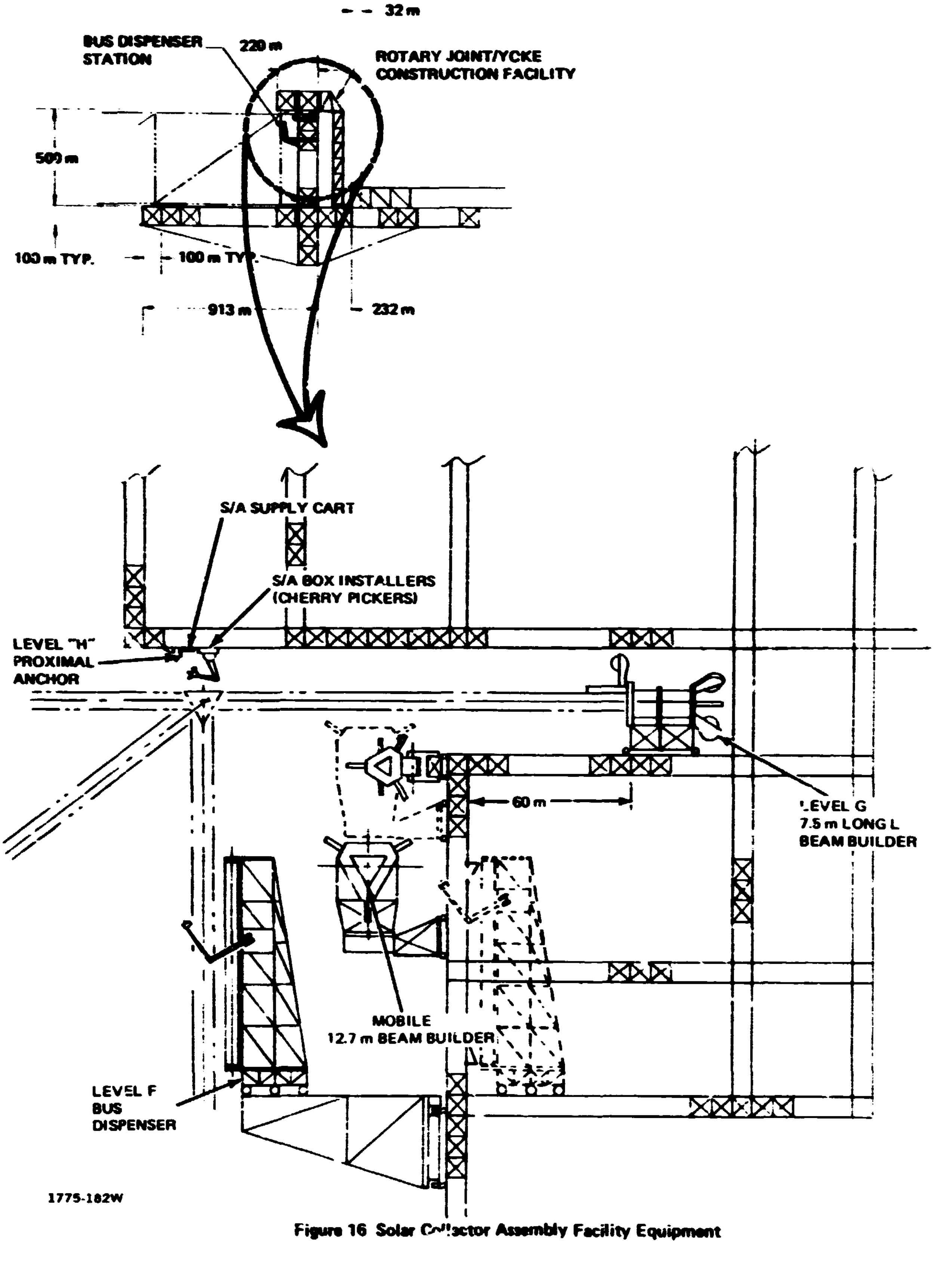

Figure 16 Solar Collector Assembly Facility Equipment

and replacement of beam builder components, while the shutdown beam builder tracks along at the same rate as the indexing structure. The figure also shows the bus dispensing station in relation to the other beam builders and the solar array anchor at level H.

- Longitudinal Beam Fabrication - In the end-builder construction concept, 10 longitudinal beam builders provide the driving force to index the satellite structure, while performing their basic function of beam-element fabrication. This end builder characteristic leads to the necessity for certain requirements, shown in Figure 17, regarding beam builder performance. Those requirements identified to date are:
  - Limit startup and shutdown accelerations to insure that beam builder subsystem machinery will safely sustain forces induced during indexing. Include the affect of the progressive mass increase in the energy conversion system structure under construction.
  - Provide for synchronized indexing. Tolerances in the simultaneously operating beam builders produce variations in beam builder forces during indexing. These variations shall be limited to safe levels, as determined by allowable forces not only on subsystem machinery, but on the construction base and energy conversion system structure as well.
  - Design for construction continuity in the event of a beam builder failure. Emphasis shall be placed on reliability of subsystem machinery including redundant operating modes, where possible, to avoid beam builder shutdown. In addition, consideration shall be given to subsystem designs that provide repair/replacement capability within 1 hour, while the shutdown beam builder tracks along at the same rate as the indexing structure. Holding fixtures to facilitate on-line/off-line maintenance and repair shall also be considered.

  It should be noted that the above requirements for limitation of accelerations and for synchronization apply to any base assembly function, where simultanity of operation is critical, including the use of multi-indexers driving simultaneously to propel the base during indexing operations. For all such functions, centralized control is necessary to limit locomotion forces to acceptable values.

- Satellite Support During Construction - As presently conceived, the L shaped facility for building the solar array carries beam machines on one leg of the L and supports the emerging structure on the other leg. As illustrated in Figure

18, disturbance of the structure already built will result in moments reacted by end loads in the beams and beam machines and by shears reacted by the supports on the other leg. The beam machines also provide the forces for indexing the structure, as it is built, by fabricating the longitudinal beams. The capability of the beam machines to provide the forces necessary to react disturbance torques and to index the assembled satellite structure requires further study.

Three options are presented in this figure for relieving the beam machines of this function. Option 1 adds on-line indexing mechanisms to the process of fabricating the longitudinal beams. These synchronized mechanisms are dedicated to indexing the beams and to reacting disturbance end loads similar to the indexers used on the single deck baseline. Shears are still reacted by the leg supports. Option 2 adds a leg to the top of the L to make a C section base. Thus, the structure has supports on two opposite faces which react all disturbance loads and index the structure. The third option extends that leg of the base, which mounts the supports. Additional supports are provided on the extension at one bay distant from the originals. These two sets of supports react all disturbance loads and index the structure.

- Solar Array Handling/Deployment - The installation of solar arrays occurs at the same work station in the base as the assembly of in-plane structural frame elements, as shown in Figure 19, to obtain maximum time-line benefits from parallel activities.

Subsequently to the installation of a 12.7 m solar array support beam, the cherrypicker removes an SA box from the supply cart and fastens it to the proximal anchor. The distal-end of the blanket is then connected to the beam. When the frame has been indexed one bay away, the blankets are fully deployed and the box is removed from its anchor support fittings and fastened to the next 12.7 m support beam to complete the cycle.

Figures 19 and 20 depict the initial operations for deploying the solar blanket from the proximal anchor on level H of the construction base. One 14.9m wide blanket is shown deployed from level H and attached to the upper lateral beam of the satellite structure. Two carriage mounted, mobile cherry pickers are also shown beginning to deploy the next solar array blanket. The cherry pickers located at each end of the blanket, as shown in Figure 20, have removed a blanket container from the supply cart and attached it to the distal

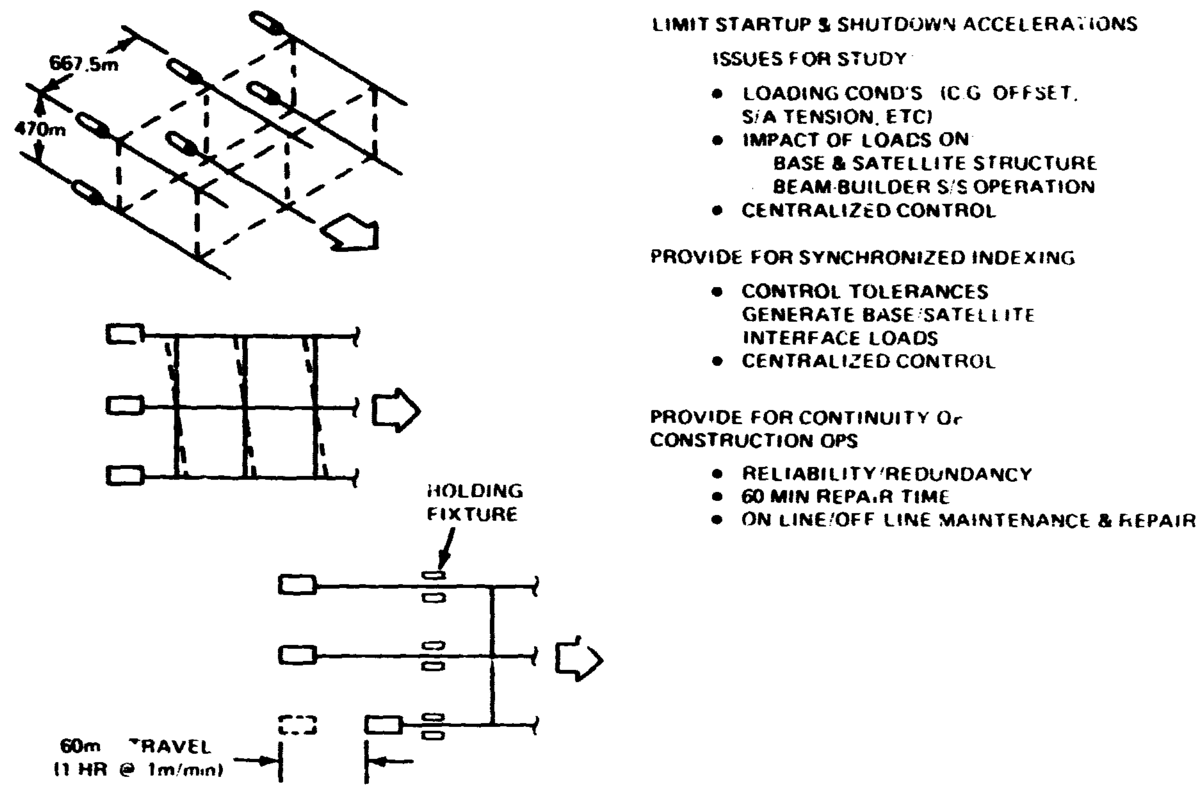

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Figure 17 Longitudinal Beam Fabrication Requirements

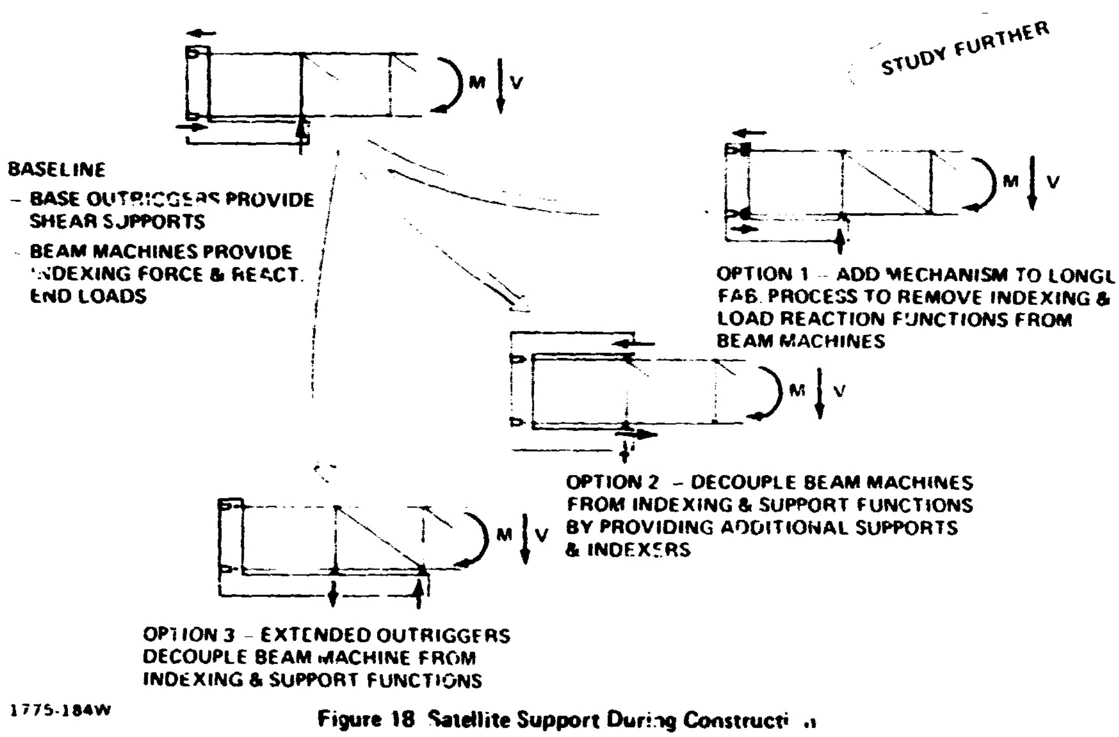

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Figure 18 Satellite Support During Construction

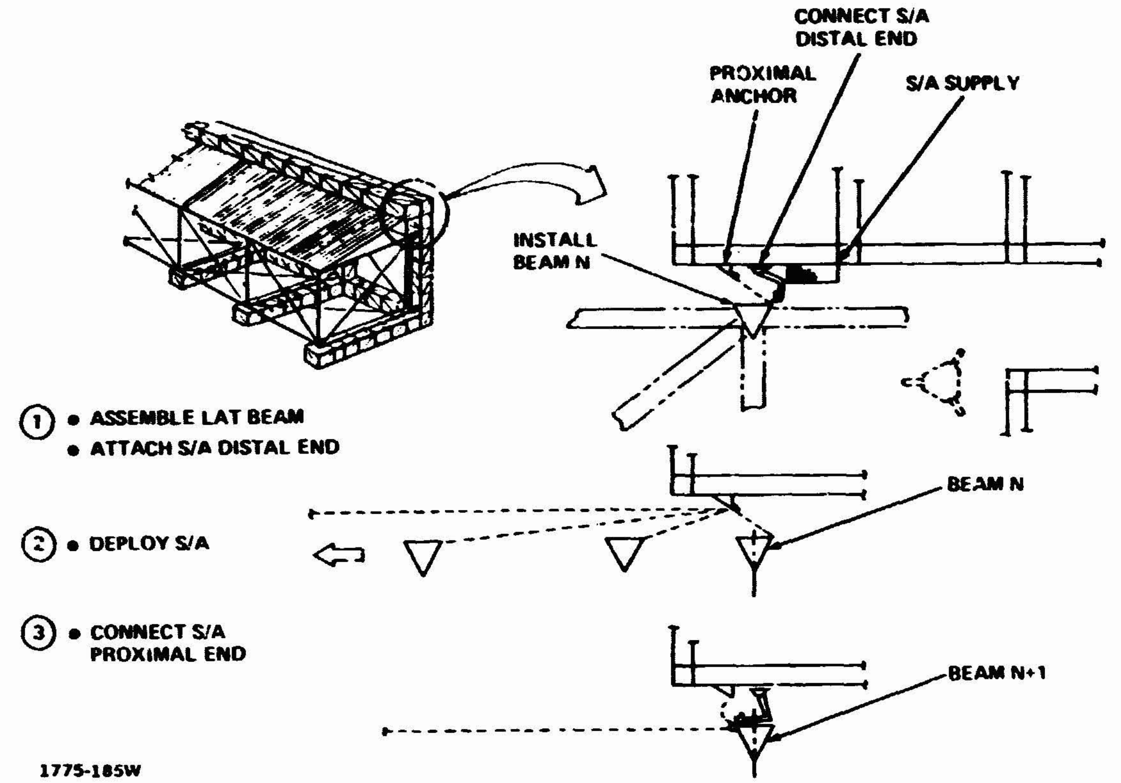

Figure 19 Coupled Frame Assembly Solar Array Deployment

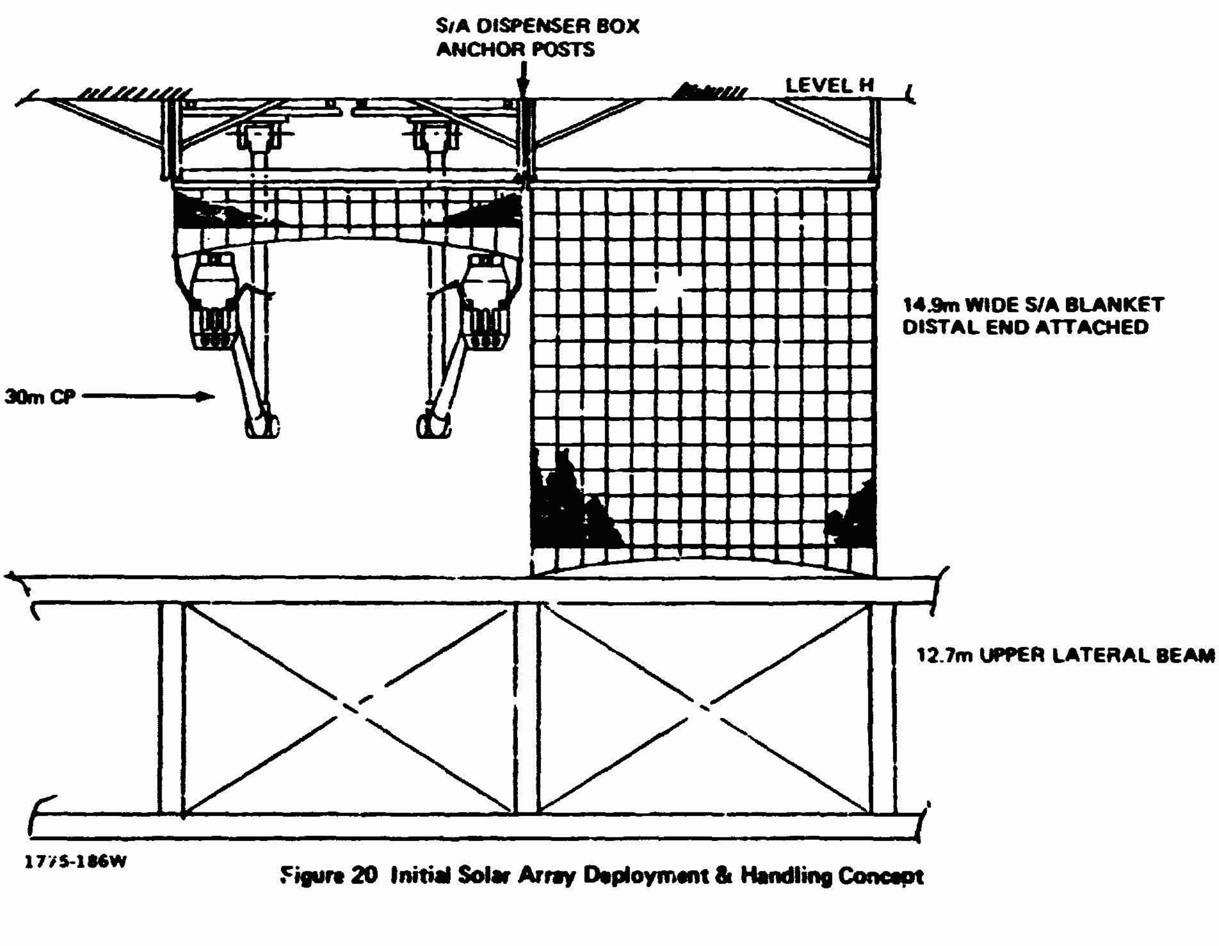

Figure 20 Initial Solar Array Deployment & Handling Concept

anchor posts. By working in unison, they remove the distal end of the blanket from the blanket container, deploy the array down to the 12.7m beam and attach the catenary and electrical leads. Both cherry pickers will then move 15m laterally and repeat the operations for the next blanket.

An overall view of the relationship of the structural fabrication and S/A panel deployment operations and their respective positions on the facility was shown previously in Figure 16.

- Power Bus Installation - The main power bus and feeder buses must be supported to allow thermal expansion and also tensioned to maintain a higher natural frequency than the primary structure. The bus dispensing concept shown in Figures 21 and 22 includes flex loops in the bus material at each vertical beam, which can permit thermal length changes to occur in bay-length increments. The tension support ties from the bus strips to structure are preloaded to maintain the natural frequency of the bus array at a level higher than that of the satellite. Thermal changes are absorbed within the elastic limits of the tension tie material without adversely affecting the preload.

  The bus arrays are supported to one side of the vertical beams and below any diagonal beams to avoid interference with these structural members. Feeder bus elements are supported at the same level as the corresponding bus element in the main or center line bus array.

  Figure 16 shows the bus dispensing machine concept. The bus dispensing machine itself is supported on a bus machine carriage, which in turn is supported on a main carriage, which moves across the base during feeder bus dispensing. The bus machine is mounted on pivots to allow orientation, as required, depending on the dispensing function.

  The bus machine can be retracted to a position, where the support of the main bus can be transferred to base structure and the machine can proceed to dispensing the feeder buses.

- Antenna Assembly Facility - Figure 23 shows a view of the solar collector and antenna assembly facility illustrating the antenna assembly area. In this view, the antenna is shown assembled and ready to be joined to the completed yoke. Adjacent to the completed antenna structure is the antenna construction facility, which is shown in greater detail in Figure 24. Mobile indexer supports, shown

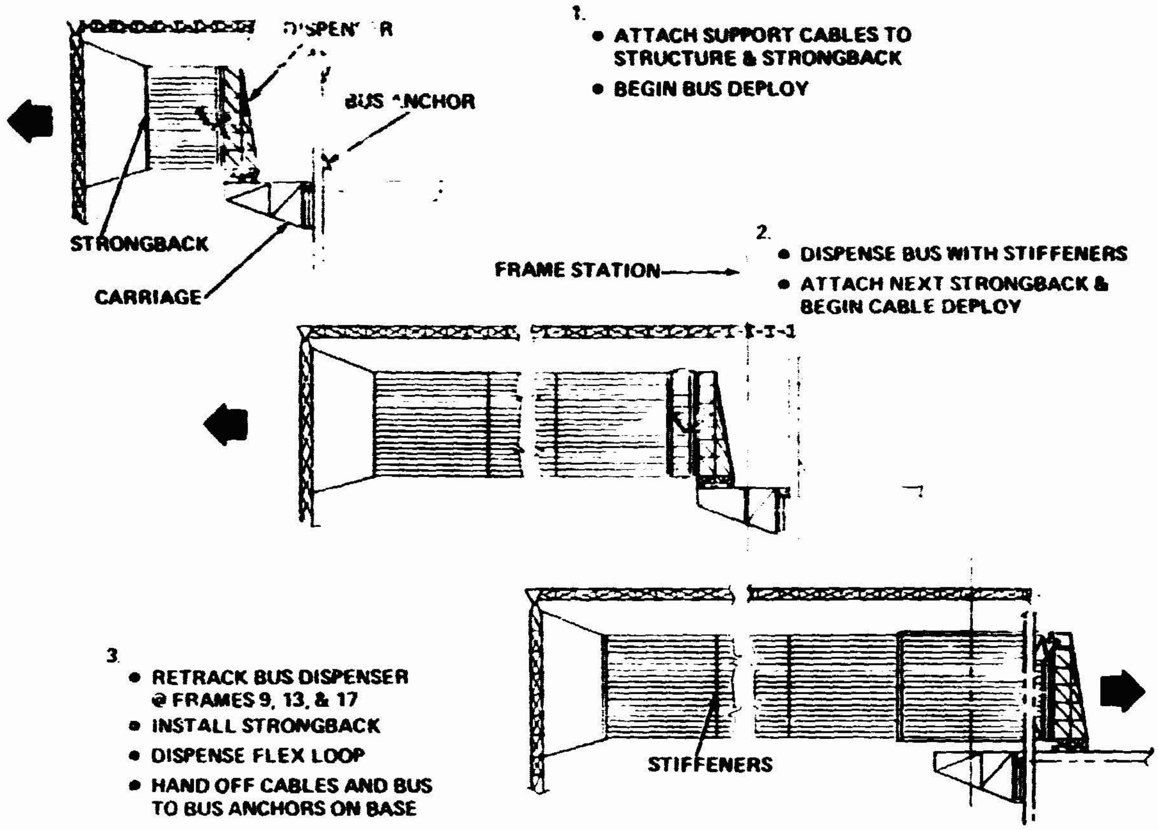

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Figure 21 Main Bus Installation Sequence (Rows 8, 12 & 16)

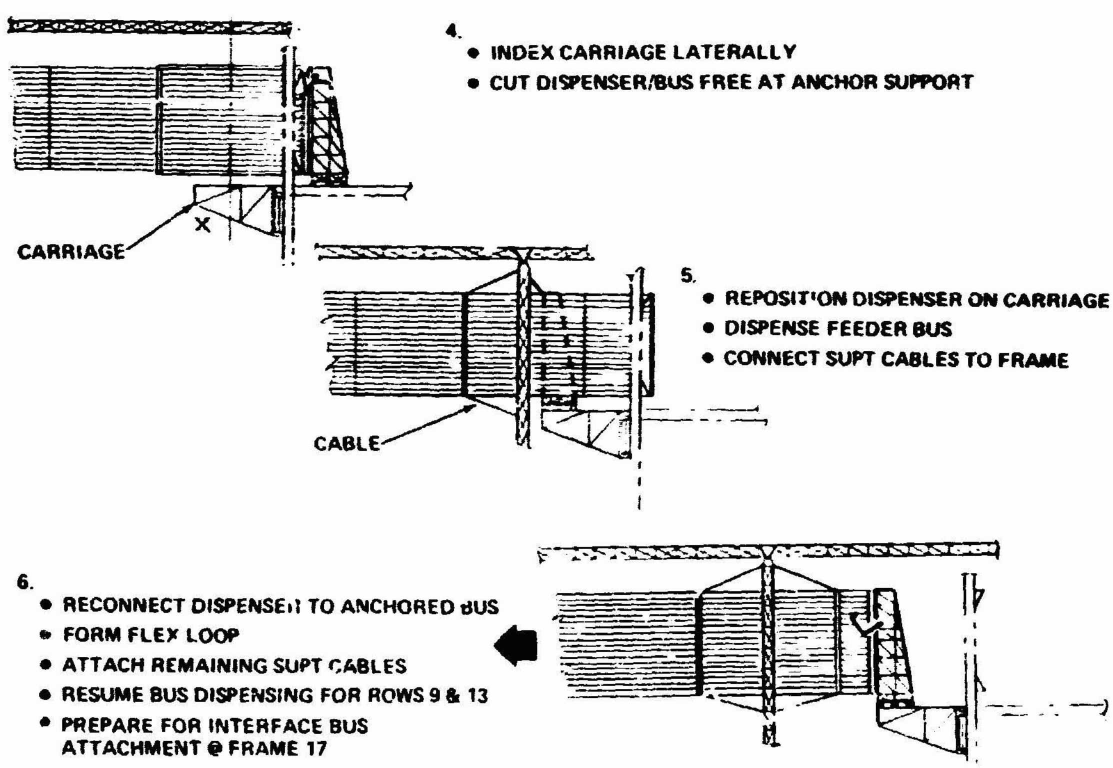

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Figure 22 Main Bus Installation (Rows 8, 12, & 16 Continued)

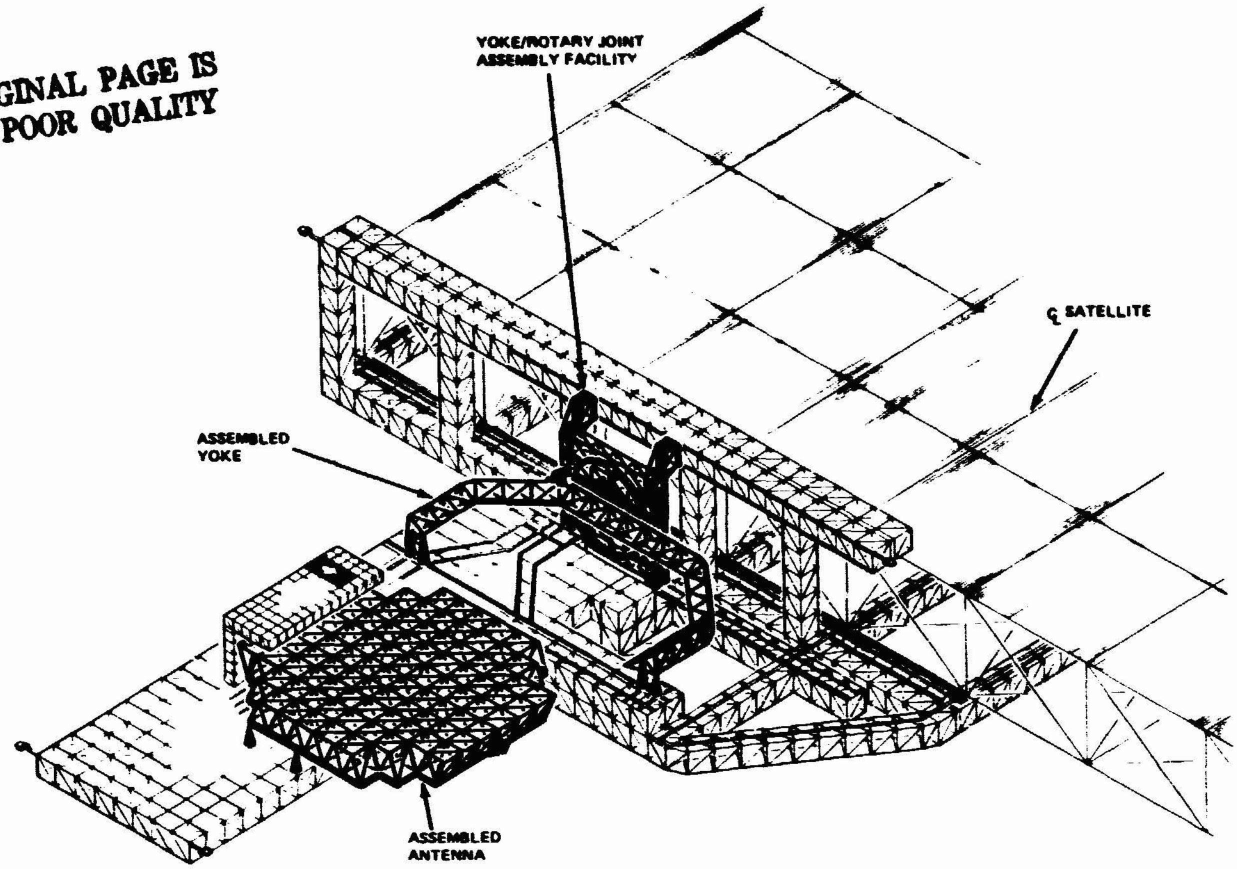

Figure 23 GEO Construction Base — Antenna Assembly Completed

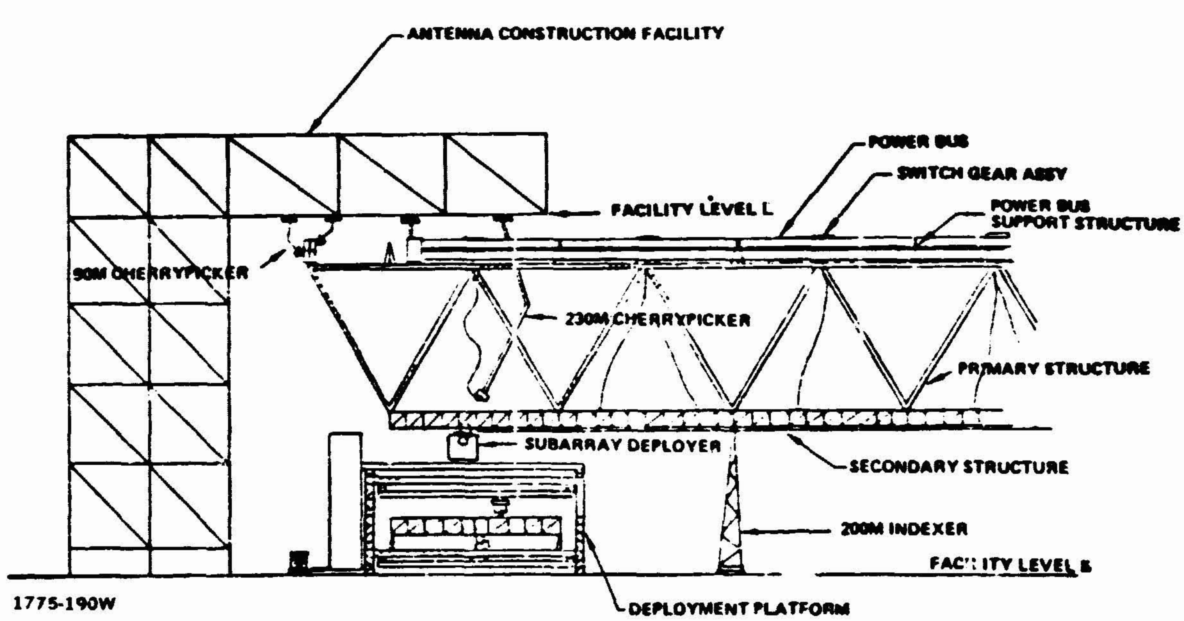

Figure 24 Antenna Construction Facility

in Figure 25, hold the antenna structure during fabrication and mating operations. Similar indexer units are also used to support the energy conversion structure during its assembly process.

2.1.2 Yoke Rotary Joint Assembly

The yoke/rotary joint assembly facility is used to construct the satellite interface system and support the mating of assembled systems. The yoke/rotary joint assembly facility is illustrated in Figures 26 and 27. This facility moves across the back of the solar collector assembly facility; first to support parallel yoke/antenna assembly operations. as shown in Figures 28 and 29, and second to facilitate final systems mating, as shown in Figure 30.

Construction materials can be supplied to the yoke/rotary joint assembly facility directly from the top of the construction base. Required materials can be moved down the face of the facility to the construction equipment operating on its face.

Further details of the facility together with its interface with the main base facility are shown in Figure 31.

2.1.3 Subassembly Factories

The subassembly factories shown in Figure 32 are included on the GEO base in order to support the main assembly operations for the antenna and solar array collector, respectively. The antenna subassembly factory on level K, for example, is equipequipped with componnet storage racks, manned cherry pickers and various subassembly jigs. This factory preassembles beam end fittings, switch gear set ups and power bus support structures for the antenna and its rotary joint/yoke interface. The level J factory provides similar subassemblies, which are tailored to be installed in the energy conversion system. The level J factory is also used to preassemble major components of the attitude control thrusters and major elements of required satellite maintenance equipment (e.g. solar array blanket annealing gentries).

2.1.4 Construction Equipment

Figure 33 illustrates typical construction equipment used by the major construction facilities of the GEO base. SPS construction equipment includes automatic machinery for fabricating large structural beams in space. These beam machines build three sided open truss beams from tightly rolled strips of composite material to avoid the higher costs incurred in transporting low density structures to GEO. General purpose manned cherry pickers, provided with dextrous manipulators, are used to assemble

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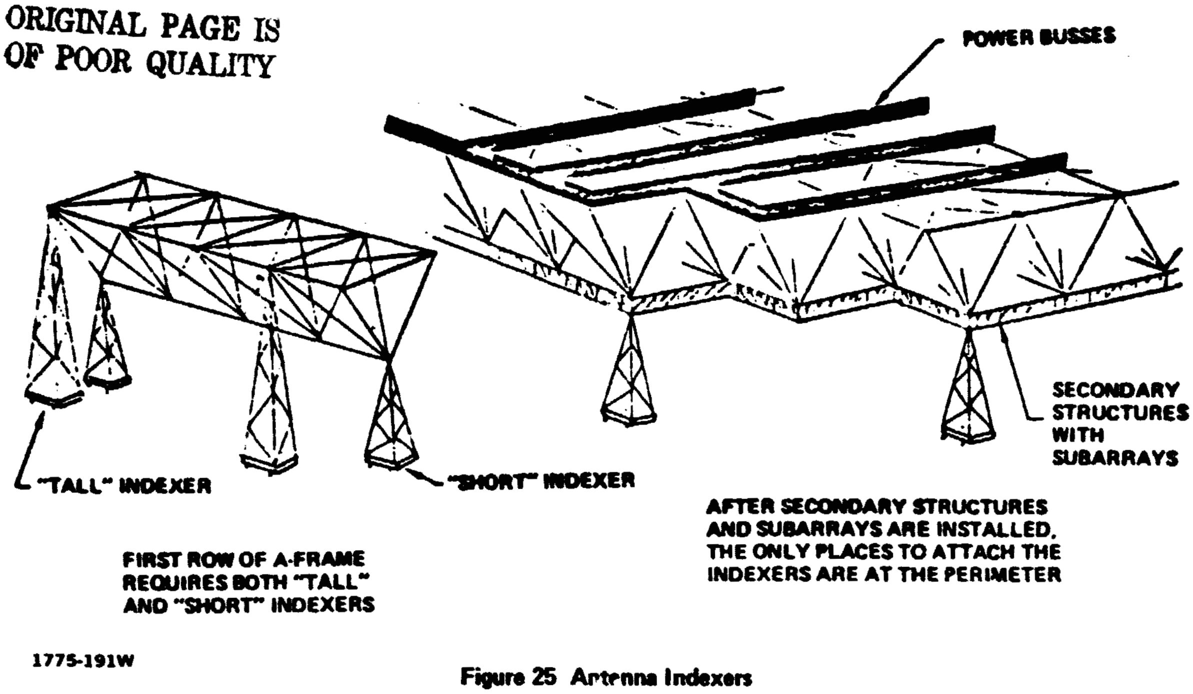


Figure 25 Antenna Indexers

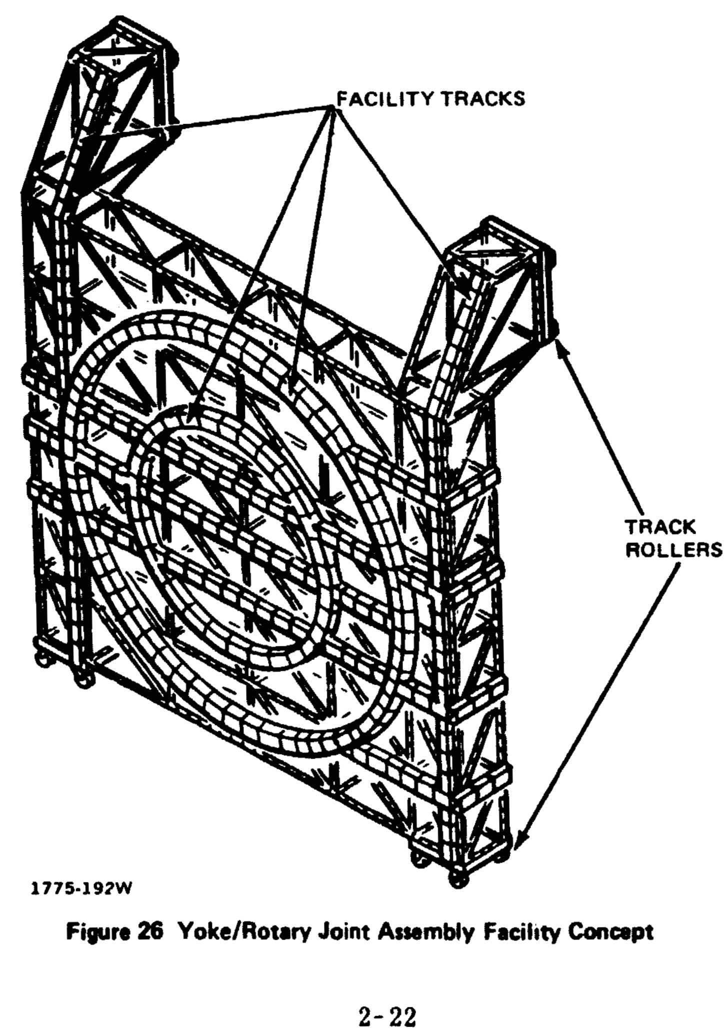


Figure 26 Yoke/Rotary Joint Assembly Facility Concept

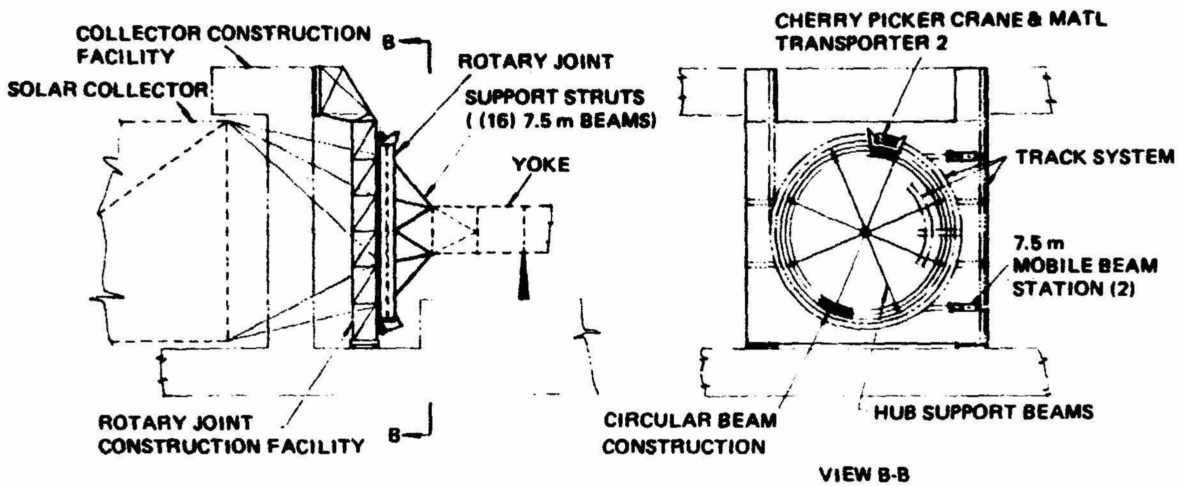
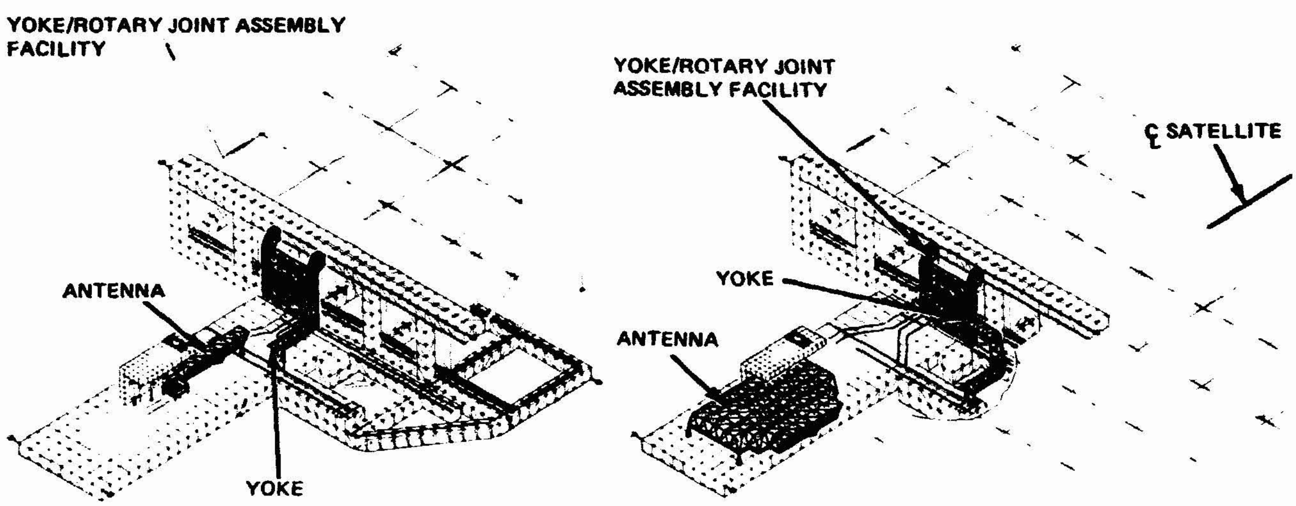


Figure 27 Yoke/Rotary Joint Assembly Facility



- FIRST CONSTRUCTION PASS
- LOCATE YOKE FACILITY FOR INITIAL CONSTRUCTION
- CONSTRUCT ANTENNA & YOKE IN PARALLEL

- SECOND CONSTRUCTION PASS
- RELOCATE YOKE FACILITY FOR CONTD USE
- ANTENNA & YOKE CONSTRUCTION NEAR MID-POINT

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Figure 28 Antenna/Interface Construction Sequence

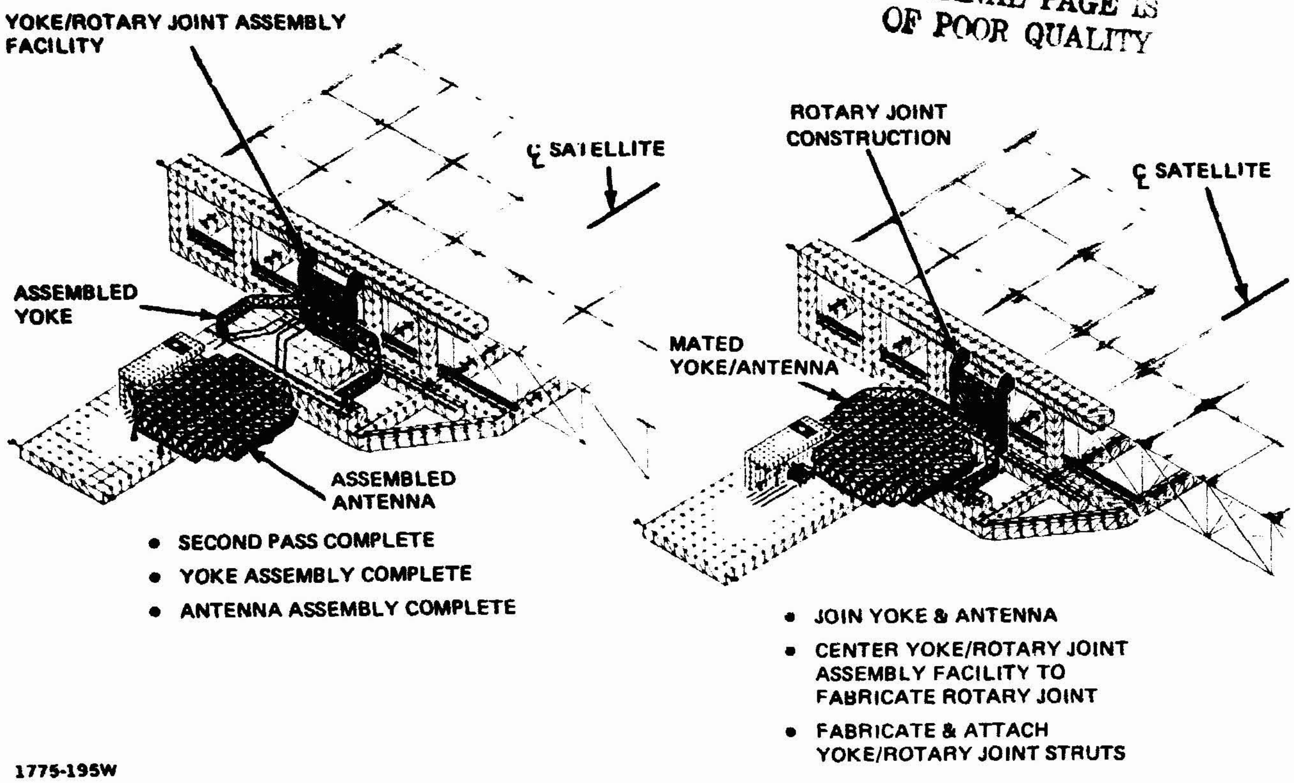


Figure 29 Antenna/Interface Construction Sequence – Continued

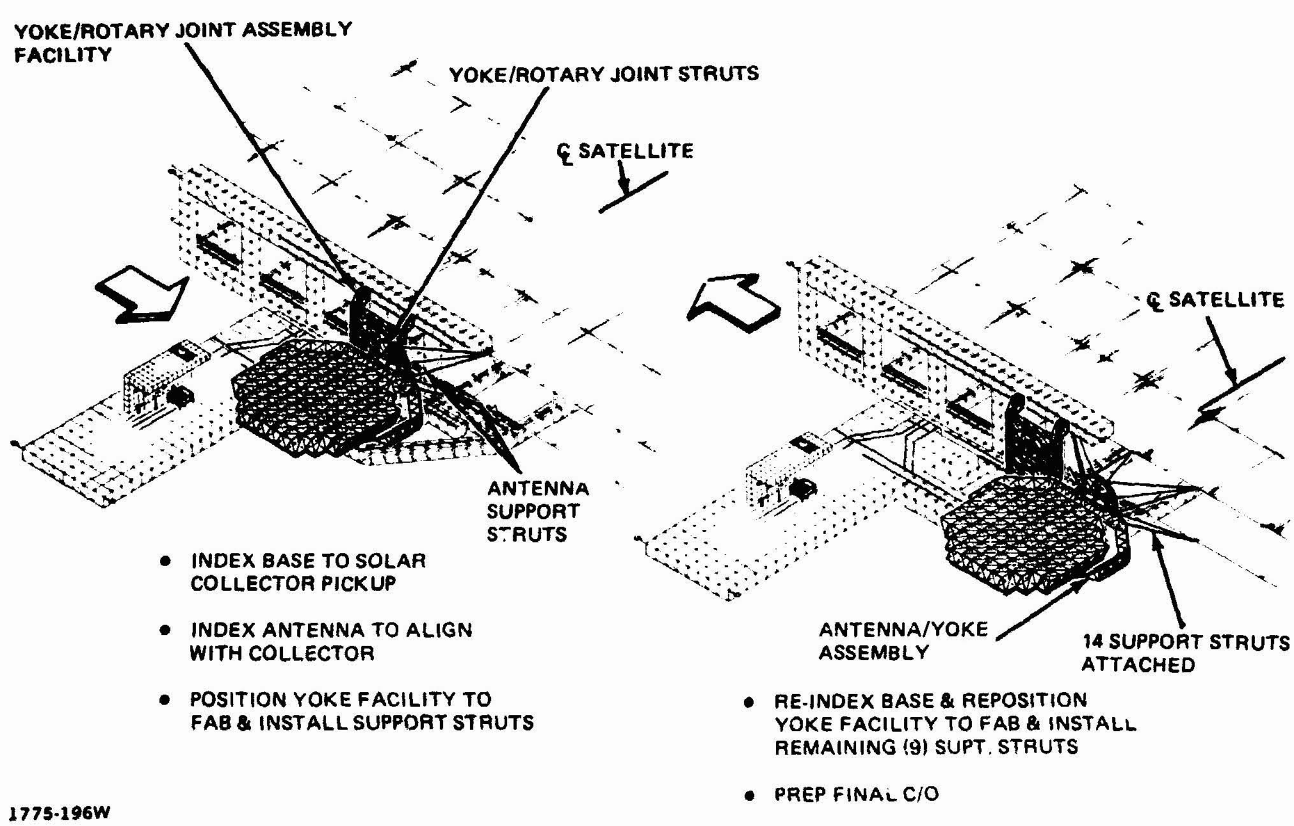
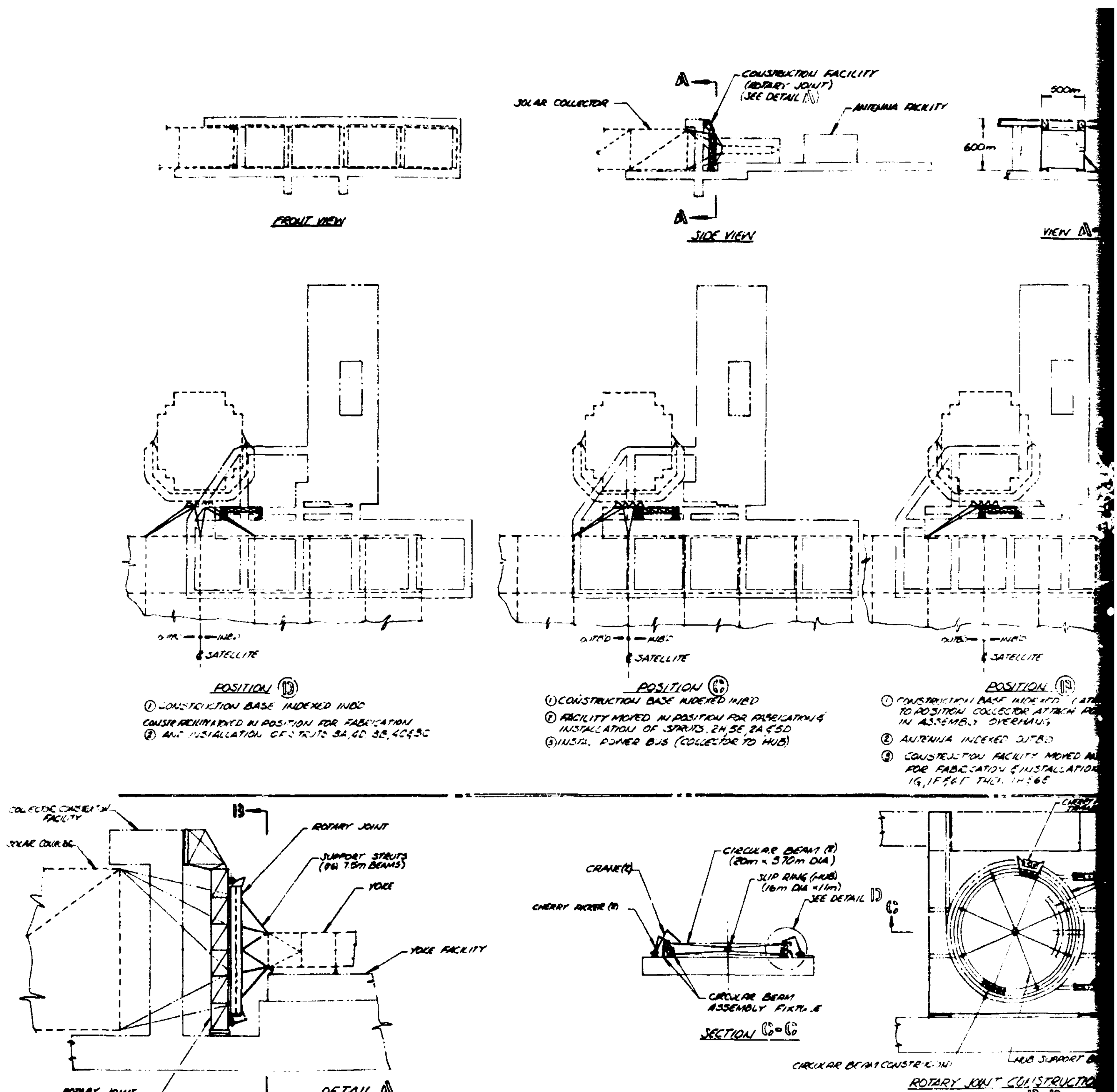


Figure 30 Final Systems Mating Operation



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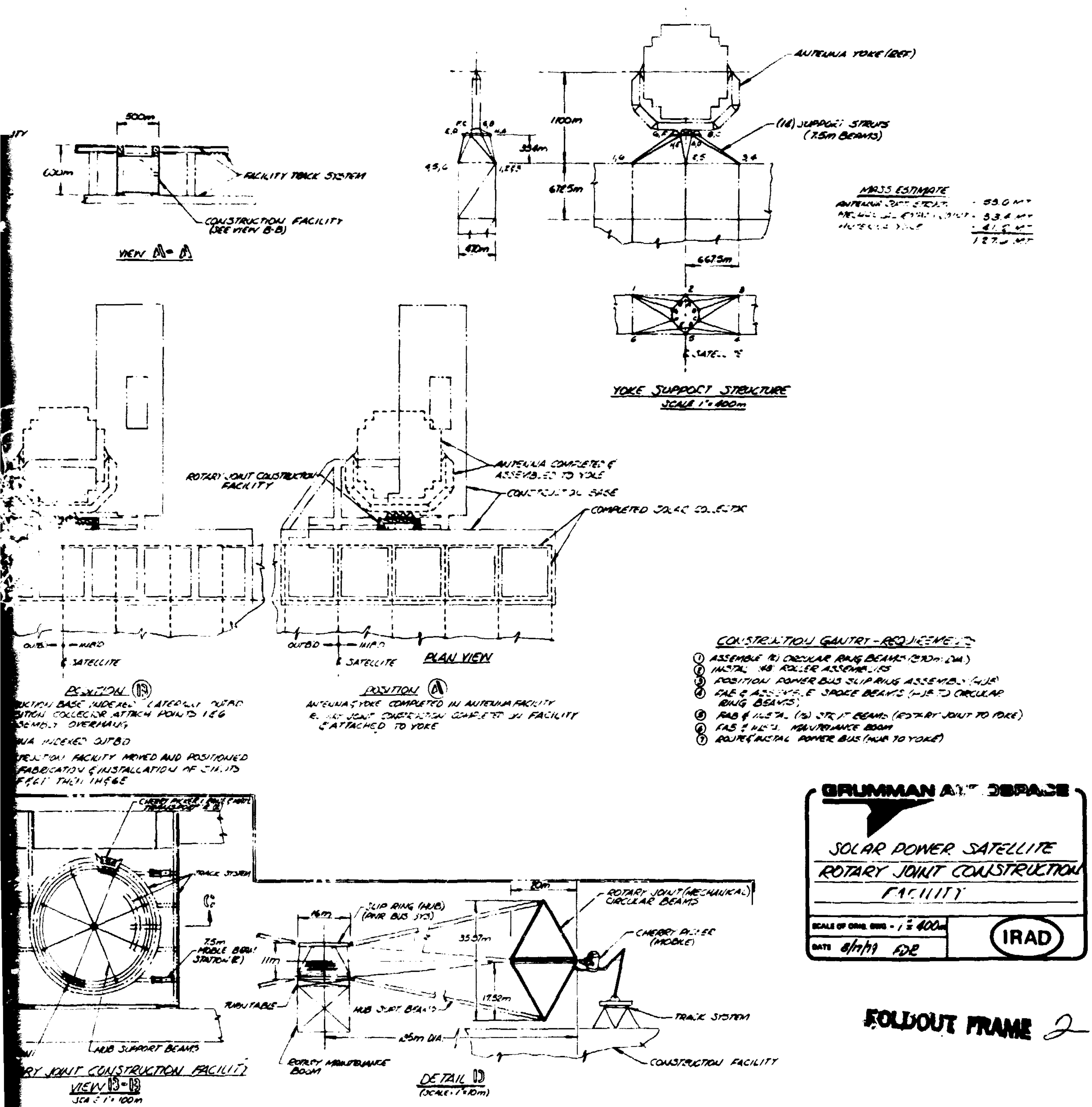

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Figure 31 Solar Power Satellite Rotary Joint Construction Facility

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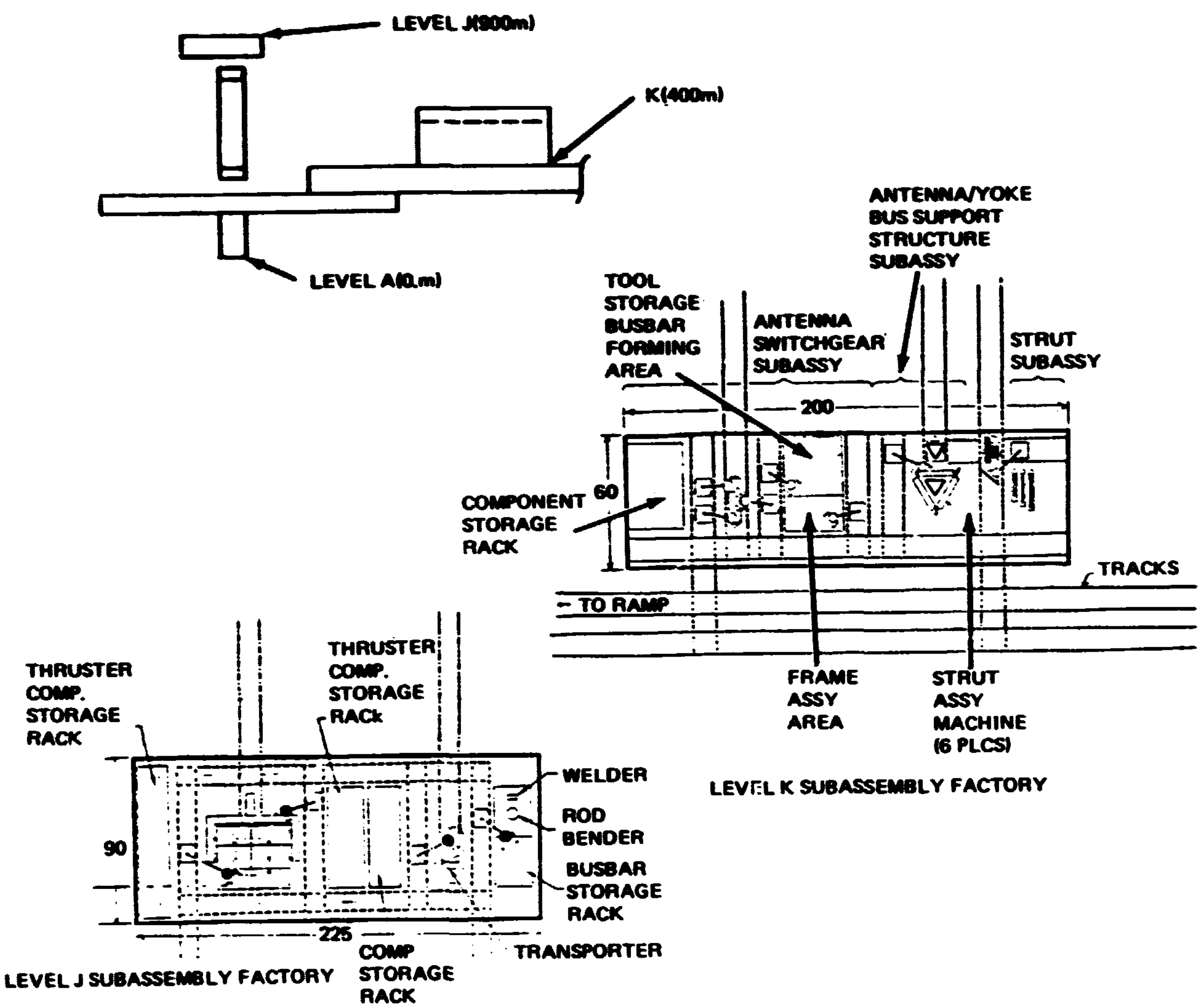

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Figure 32 Subassembly Factories

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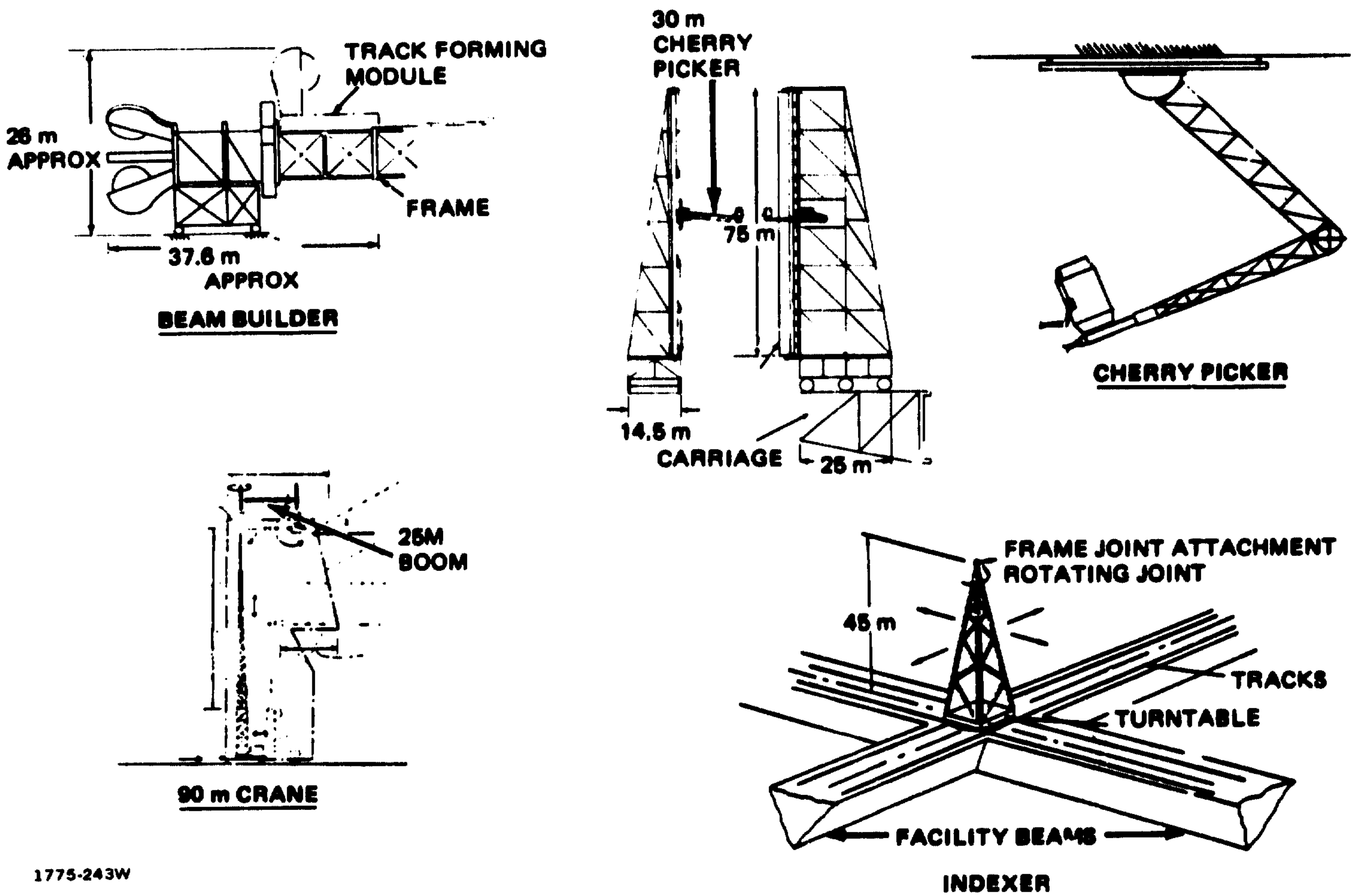

Figure 33 Typical Construction Equipment

these light weight beams and install the required subsystem components in the energy conversion and power transmission systems. During construction, the major elements of the satellite are supported by indexers, which can be moved across the base as needed. Additional equipment is also provided to facilitate the deployment of large sheet metal power buses, anchoring solar array blanket containers, and installing antenna systems.

Table 1 provides a summary listing of the major equipment types and where they are used on the base.

The solar collector beam builder substations, power bus dispenser station and antenna deployment platform are discussed further below.

2.1.4.1 - Energy Conversion Beam Builder Requirements - Four different types of beam builders are required to construct the energy conversion system, as shown in Table 2. Two types of beam builders are synchronized for continuous longitudinal beam fabrication, while the remaining two beam builders are employed to fabricate lateral, vertical, and diagonal bracing members. The 7.5 m synchronized and 12.7 m autonomous beam builders, which operate at the solar array level, are required to install solar array maintenance track during beam fabrication. The longitudinal beam builders must also be able to install attachment frames for joining other beams. The varied functions of the synchronized, upper level, longitudinal beam builders are depicted in Figure 34. All segmented beams, in turn, must be fabricated with suitable end attachments:

- 7.5 m Beam Builder Substations - The 7.5 m synchronized substation, illustrated in Figure 35, includes a beam machine equipped with frame-making features. Frame segment supply canisters are mounted at each beam face at cross member attaching stations. Since current maintenance track concepts call for supports at each cross member, track attachment will occur after the completed cross members emerge from the beam machine. This requirement dictates the location of the track forming module as shown.

  The 7.5 m mobile substation illustrated in the lower part of the figure, uses a beam machine provided with end fitting attachment features. A column mounted end fitting support fixture with movable gripping fingers can rotate to place fittings on either end of a beam. The column swings down, as required, to clear the emerging beam or pick up an end fitting from the supply cannister. The grip is capable of extending to secure and withdraw a

TABLE 1 CONSTRUCTION EQUIPMENT SUMMARY

ITEM	QTY* M	A	Y	T	MASS (10^3 kg) EA.	SUB TOTAL
WBS 1.2.1.1.2.1 BEAM MACHINES						
• 7.5 m SYNCH TRAVEL	10			10	11	110
• 7.5 m GIM. MOBILE, MANNED	2	2	2	6	15	90
• 12.7 m GIM. MOBILE, MANNED	1			1	21	21
WBS 1.2.1.1.2.2 CHERRY PICKERS						
• 30 m	8		2	10	2.5	25
• 90 m	4	2		6	5	30
• 120 m		2	1	3	7	21
• 250 m		1		1	9	9
WBS 1.2.1.1.2.3 INDEXERS						
• 15-45 m	5			5	1.3	6.5
• 130 m		6	8	14	3.0	42
• 230 m		2		2	5.5	11
WBS 1.2.1.1.2.4 BUS DEPLOYER						
• 90 m (ALSO 80 m)	1	1	1	3	8.0	24
WBS 1.2.1.1.2.5 SOLAR ARRAY DEPLOYMENT EQUIPMENT						
• PROXIMAL ANCHORS	176			176	TBD	TBD
WBS 1.2.1.1.2.6 ANTENNA DEPLOYMENT PLATFORM		1		1	28	28
ADD 10% ALLOWANCE FOR UNDEFINED EQUIPMENT						42
*USED ON M-SOLAR ARRAY SYSTEM A-ANTENNA Y-YOKE & ROTARY JOINT T-TOTAL 1775-203W						

TABLE 2 ENERGY CONVERSION BEAM BUILDER SUBSTATION REQUIREMENTS

TYPE MACHINE	7.5 m SYNCHRONIZED W TRACK	7.5 m SYNCHRONIZED W O TRACK	12.7 m AUTONOMOUS W TRACK	7.5 m AUTONOMOUS W O TRACK
USE	UPPER (SOLAR ARRAY) LONGITUDINALS	LOWER LONG BEAMS	UPPER (SOLAR ARRAY) LATERALS	ALL OTHER BEAMS
FUNCTIONS	• FAB 7.5 m CONTINUOUS BEAM W FRAMES & TRK • NOMINAL FIXED • REMOTE CTL	• FAB 7.5 m CONTINUOUS BEAM W/FRAMES • NOMINAL FIXED • REMOTE CTL	• FAB 12.7 m BEAM W END FITTINGS & TRACKS • ATTACH ACQ BUS & JUMPERS • MOBILE & GIMBALED • ON BD OPER	• FAB 7.5 m BEAM (VARIOUS LENGTHS) W END FITTINGS • MOBILE & GIMBALED • ON BD OPER
MACHINES	5	5	1	2
FAB RATE	3.5 m min	3.5 m min	5 m min	5 m min
BEAM MATL CAPACITY	10,800 m	10,800 m	10,700 m	10,200 m
GIMBAL CAPACITY	TBD	TBD	YAW · 90°	YAW · 90° PITCH 90°
TRAVEL	3.5 m min	3.5 m min	20 m min	20 m min

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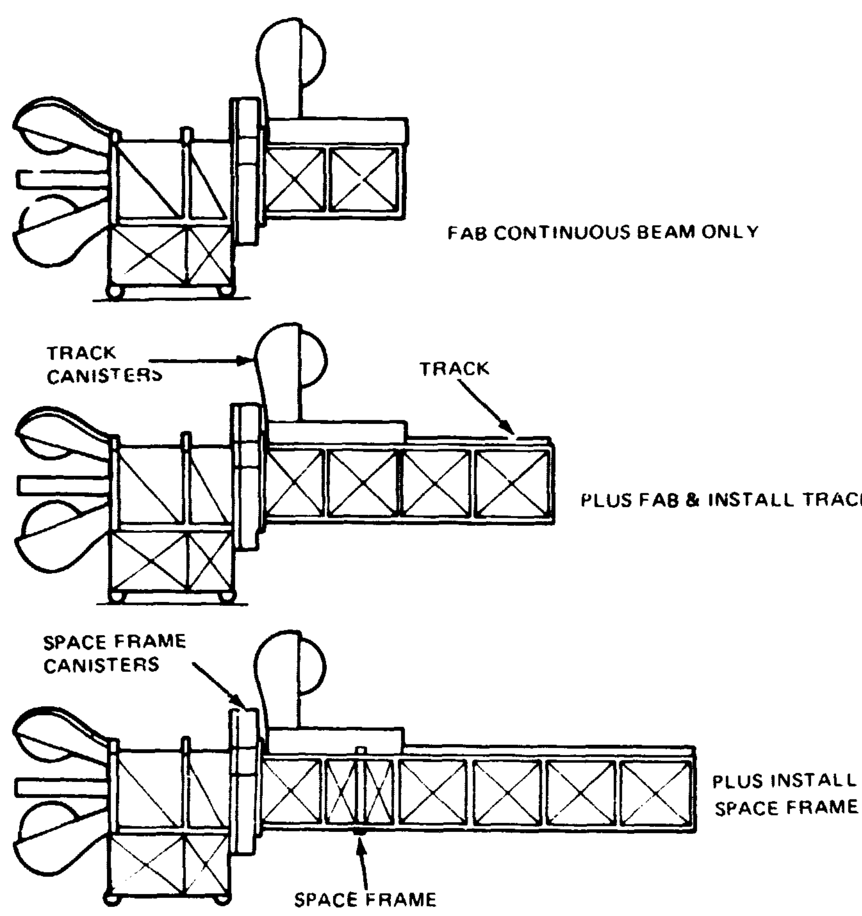

Figure 34 Longitudinal Beam Machine Fabrication Modes

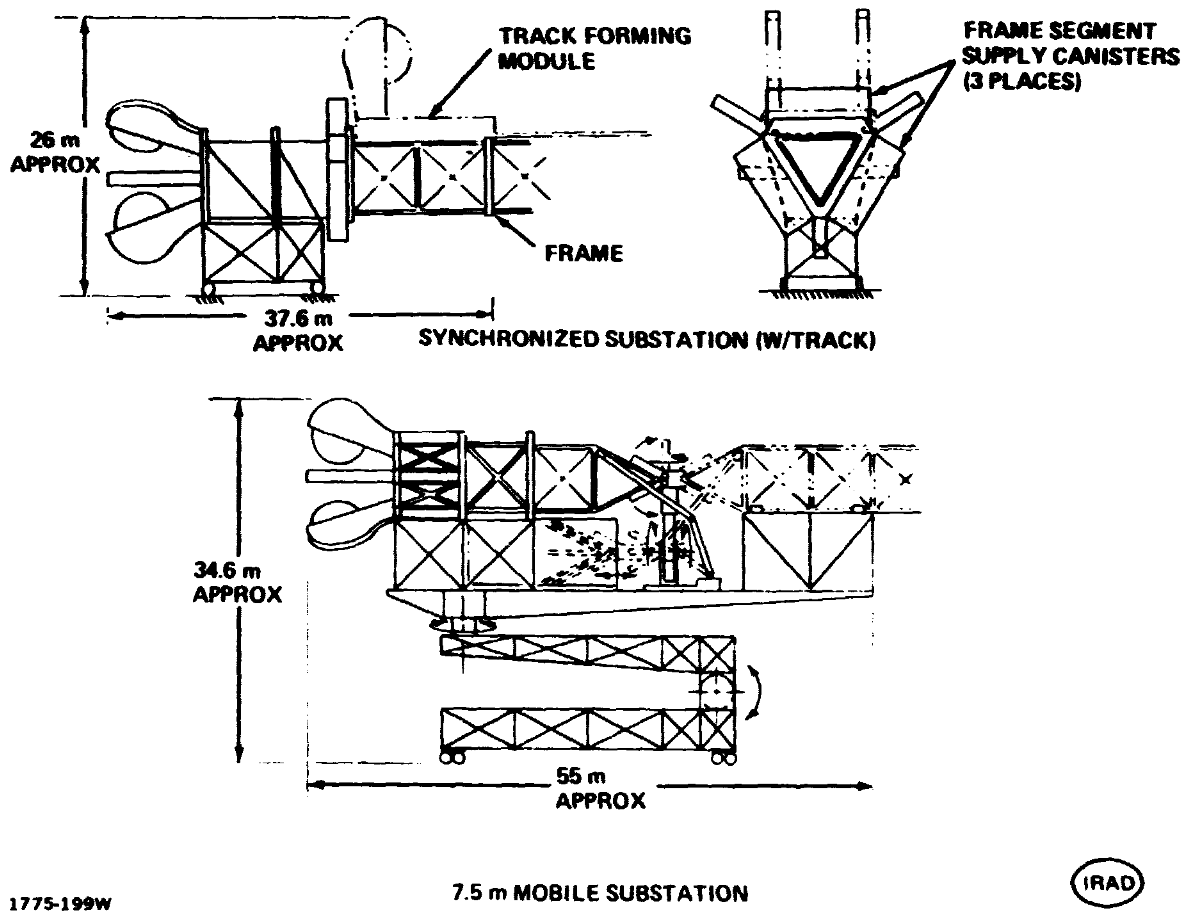

Figure 35 7.5 m Beam Builder Substations

fitting from the supply canister. An automatic arm attaches the end fittings to the beam on either end, as required. An accessory platform is equipped with holding devices which index the completed beam and position it for installation of the end fitting after it has emerged from the beam machine. The entire platform with beam machine and accessories is capable of 360° swiveling and can be rotated perpendicular to the carriage to provide any required orientation.

- 12.7 m Beam Builder/Acquisition Bus Substation - The 12.7 m beam builder concept, shown in Figure 36, has multiple functions in addition to the basic beam fabrication:
  - The entire sub-station platform can be oriented to direct the fabricated beam as required.
  - Maintenance tracks are installed on the top and side of the beam during fabrication.
  - An end fitting fixture can take pre-fabbed end fittings from a supply canister and install them on either end of the beam with the aid of the end fitting installer.
  - Acquisition and jumper buses are installed during beam fabrication as needed.
  - Catenary attach fittings and S/A interbay jumpers are installed during beam fabrication.
  - A support platform equipped with indexers holds the beam to maintain alignment during fabrication and end fitting installation and aids in positioning the completed beam.

2.1.4.2 - Mobile Power Bus Dispensing Station - The power bus dispensing station, shown in Figure 37, dispenses both main and feeder buses and installs the bus support cables. Individual bus strips are supplied by specific supply canisters mounted at the back of the dispensing unit. The support cables are supplied by drums mounted on the top and bottom of the dispensing unit. The entire dispensing module pivots to dispense either feeder or main bus as required. The dispensing unit is supported on a base, which travels on the main carriage. The main carriage moves the entire assembly from one end of the construction base to the other during feeder bus dispensing.

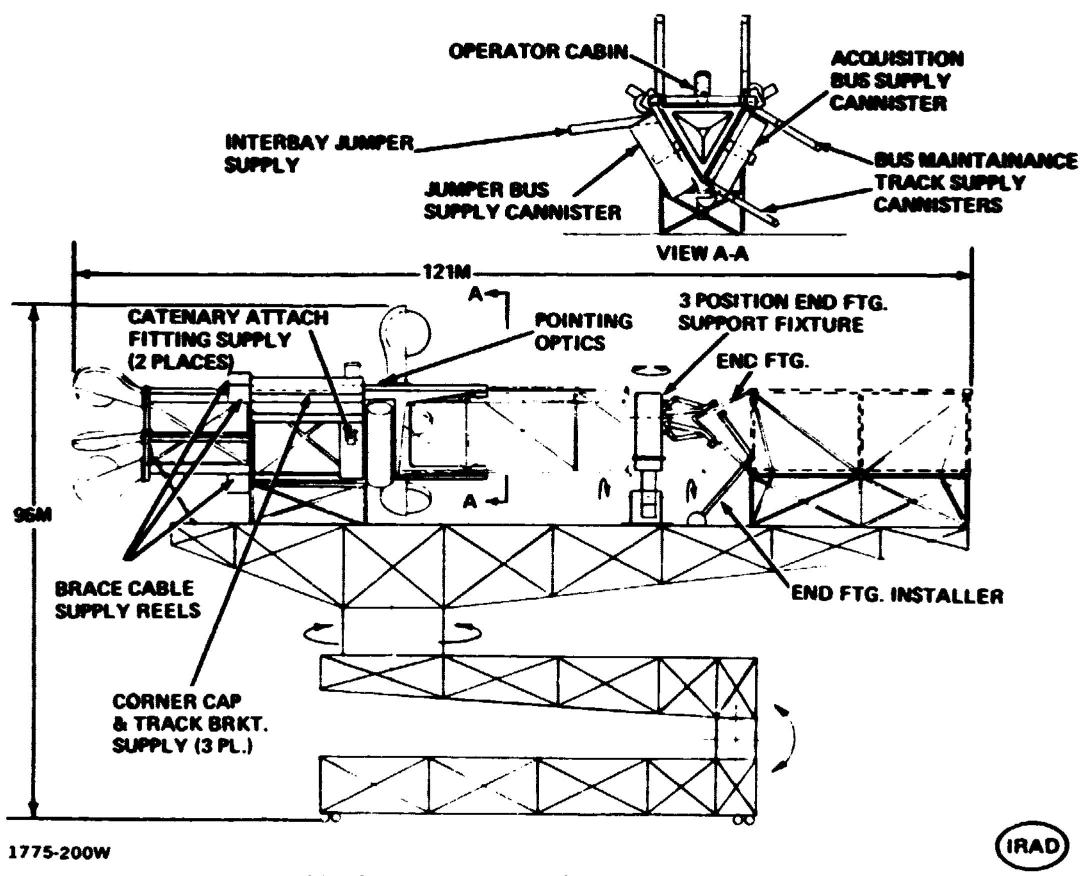

Figure 36 12.7 m Beam Builder/Acquisition Bus Substation

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REQUIREMENTS

- DISPENSE MAIN & FEEDER BUSES IN SEQUENCE
- CUT AND SPLICE BUS MATERIAL
- INSTALL STIFFENERS & STRONGBACKS
- INSTALL AND PRELOAD CABLES

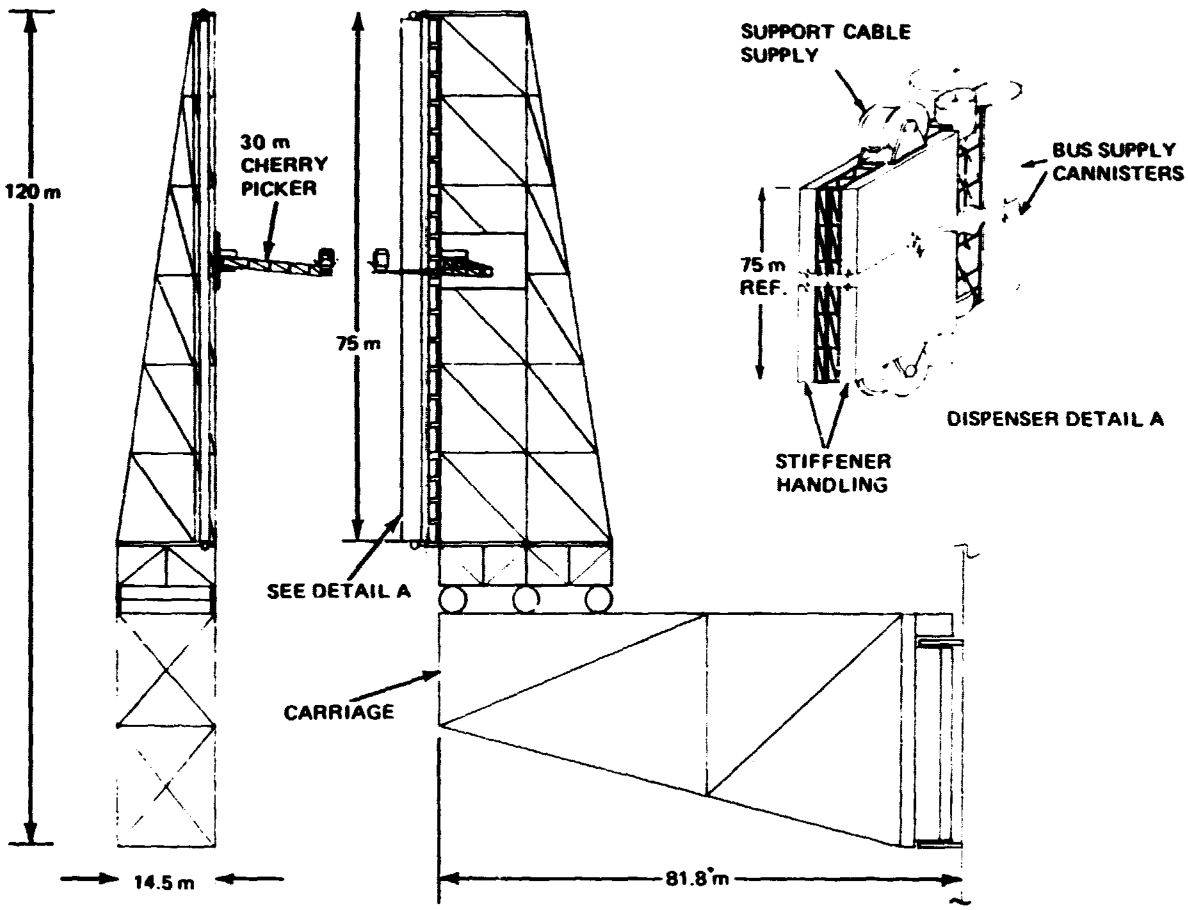

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Figure 37 Mobile Power Bus Dispensing Station

Aided by a dedicated, mobile cherry picker, the bus dispensing station installs and preloads the supports cables on the array as part of the dispensing operation. The support strongbacks and intermediate stiffeners are installed while the bus array is still secured by the dispensor. The dispensing station provides the correct mix of bus array elements to meet main and feeder bus requirements in the correct sequence in the construction process. The dispensing station can cut and splice bus material as required.

During main bus dispensing operations, the dispensing station is positioned at one end of the construction base.

2.1.4.3 - Antenna Deployment Platform - The antenna deployment platform, as defined by Boeing, is shown in Figure 38.

This platform, the most prominent assembly of equipment on the antenna construction facility, is used to deploy the secondary structure, install phase control wiring, install power distribution wiring, and to install subarrays.

2.2 GEO BASE LEVEL 'J' FACILITIES ARRANGEMENT

The center of GEO base logistics activities occurs at level 'J', as shown in Figure 39, which identifies the following activity areas.

- Staging Area - This area is located over the vertical columns of the factory. Sorted and subassembled hardware are stored here until required in the lower construction areas. Loaded flatcars are moved onto vertical lift elevators and then travel down to the appropriate lower construction level work site. The staging area is duplicated in five locations, as noted.
- Cargo Docking/Unloading/Sorting Center - The KTM modules and Cargo Pallets are landed here and unloaded onto railroad flatcars for delivery to their next station.
- Subassembly Factory - The hardware in the Cargo Pallets is delivered to this area for subassembly work prior to its movement to the lower levels for installation.
- Crew Quarters/Operations Center - This center includes the base habitats and areas for habitat growth.
  - Satellite Service Habitat Growth Area - This area has been reserved for growth, when 40 satellites are being services. This area will be identical in configuration to the habitat area used for servicing 20 satellites.

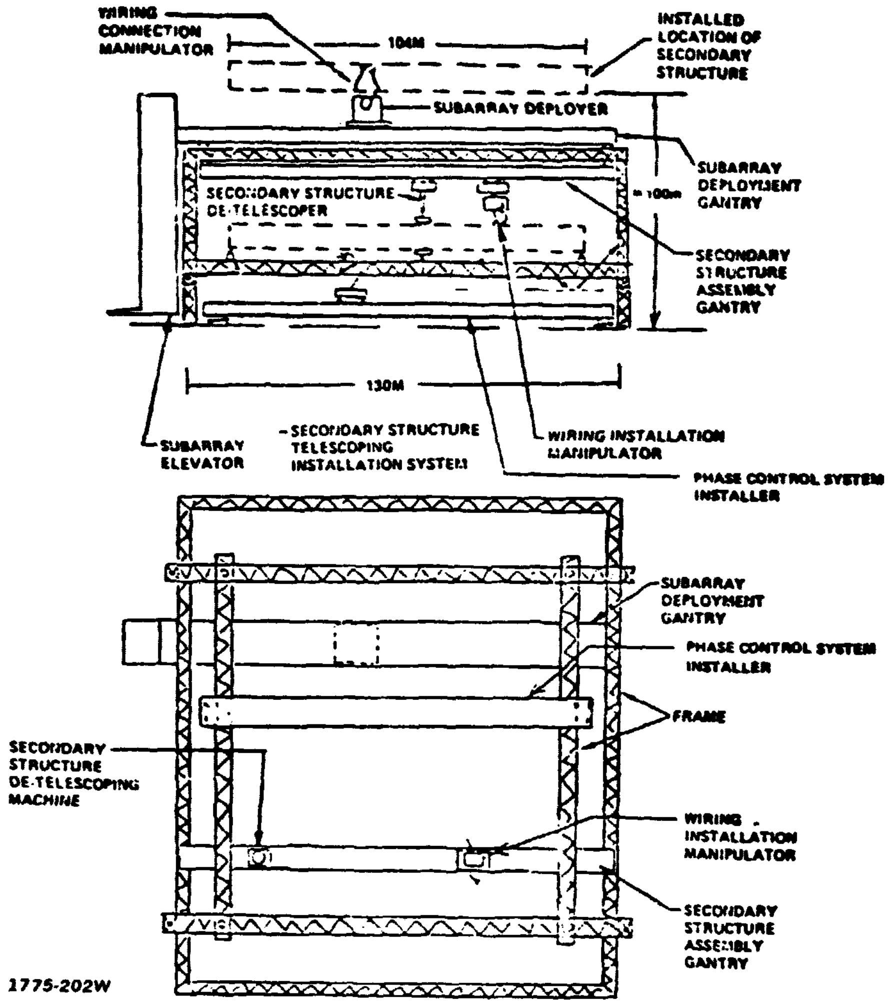

Figure 38 Antenna Deployment Platform

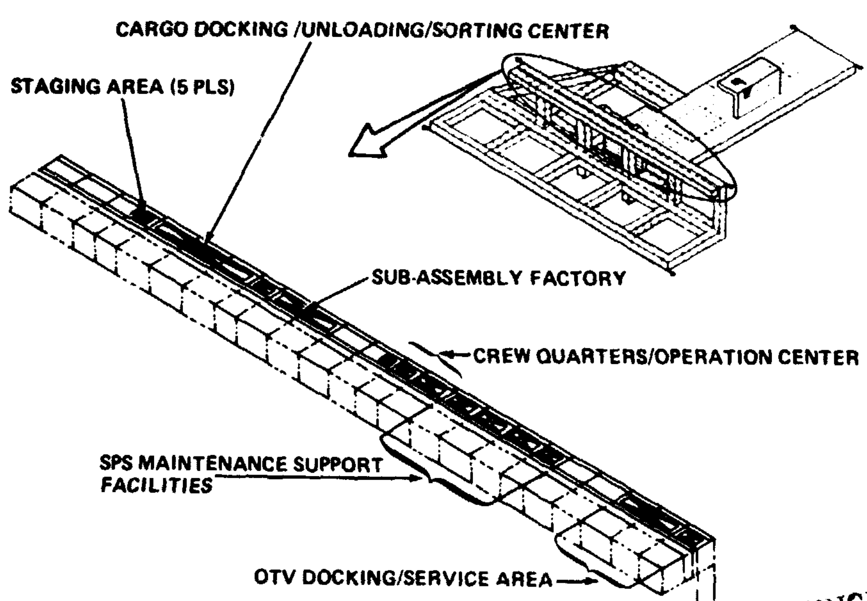

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Figure 39 GEO Base Level 'J' Facility Arrangement

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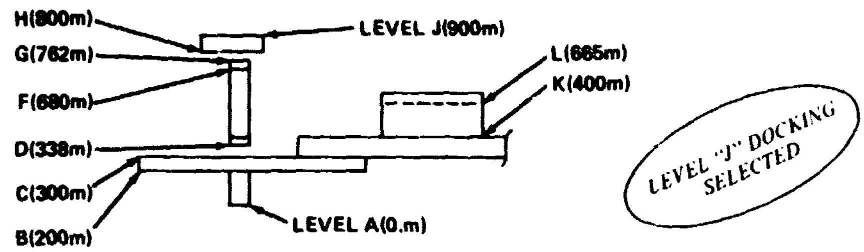
- Base Construction Habitats & Satellite Service Habitats - This area contains two functional complexes. One area consists of four (4) habitats, one (1) interim habitat and one (1) control center. The other area contains four (4) habitats and one (1) interim habitat. The first complex is used to house and control the base construction personnel and the other for satellite service personnel.

- SPS Maintenance Support Facilities - This complex includes satellite refurbishment factories and component storage.
  - Reconditioned Component Storage - Those components, which have been reconditioned and repaired in the KTM & Miscellaneous Component Refurbishment Factories, are stored here until needed.
  - KTM Refurbishment Factory - All defective klystrons from the outlying SPS stations are brought into this module for refurbishment.
  - Miscellaneous Component Refurbishment Factory - This module has facilities within it for refurbishment of electrical, electronic and mechanical devices. Components are disassembled and assembled, as well as tested, in this area.
  - Defective Component Storage - Those components, which have to be reconditioned and repaired, are stored here. When room and scheduling permits, they are transported from here to the Refurbishment Factories.

- OTV/POTV Docking/Service Area - Sufficient docking pads are located here for the landing of POTVs and OTVs. Quantities of propellant for refueling the OTVs are also stored here.

Figure 40 lists the total weight of material that has to be delivered to the GEO Base for construction of an SPS. It can be seen that over half of the material landed on the base has to be delivered to Level H for use in assembling the energy conversion system and solar blankets. Two levels were considered as docking areas for delivery of personnel and material. Based on this chart, it is apparent the logistics system is greatly simplified by using Level J for the docking area.

Figure 41 shows the overall GEO base cargo handling and distribution flow. All material arriving from LEO is delivered by EOTV and transferred to the GEO base by a dedicated cargo tug. The tug lifts a cargo or KTM pallet from the EOTV and flies it over to the base cargo docking area. Construction materials, base supplies, OTV supplies and SPS maintenance parts are unloaded onto waiting railroad flat cars adjacent



FACTORY LEVEL	CONSTRUCTION OPERATION	TOTAL MAT'L MT	RATE MAT'L USED	INTER LEVEL MASS DISTANCE 10^8 kg-m	
				"B"-DOCK	"J"-DOCK
	ENERGY CONVERSION ASSEMBLY				
H	– SOLAR BLANKET INSTALLATION	23185	725MT/4DAYS	139.1	23.18
G	– STRUCTURE FAB & ASSY	1731	398MT PLUS 42MT/4 DAYS	9.72	2.38
F	– STRUCTURE FAB & POWER BUS INSTL	1845	58MT/4 DAYS	8.86	4.06
D	– STRUCTURE FAB & ASSY	1731	398MT PLUS 42MT/4 DAYS	2.39	9.72
	POWER TRANSMISSION ASSEMBLY				
K	– STRUCT FAB & ASSY & SUBARRAY INSTL	9953	83MT/DAY	19.91	69.67
L	– STRUCT FAB & ASSY & PWR BUS INSTL	2558	21MT/DAY	11.89	24.68
	TOTAL	41000MT		191.87	133.69

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Figure 40 GEO Base Interlevel Material Transfer Requirements

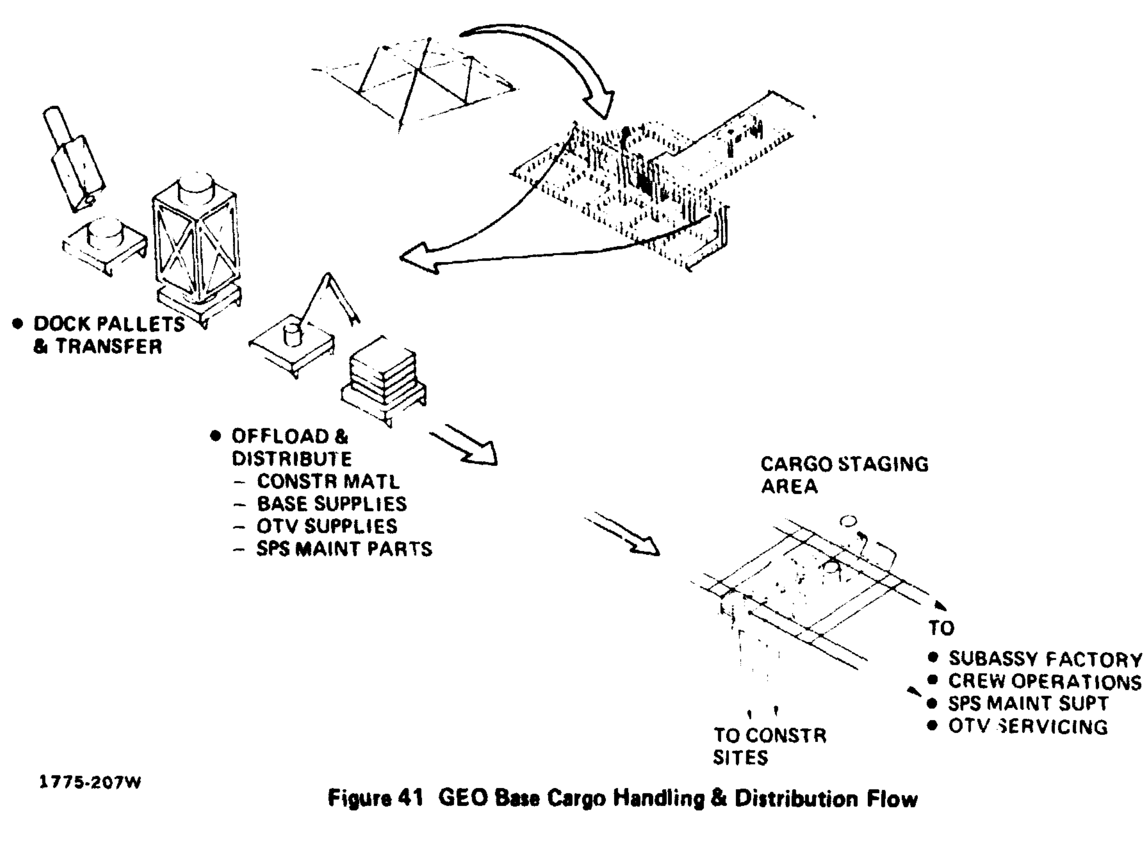

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Figure 41 GEO Base Cargo Handling & Distribution Flow

to the docking area. The loaded flat cars are moved onto mainline track to one of five (5) cargo staging areas. When required, the flat car, loaded with construction materials, is moved out of the staging area onto either forward or aft facing vertical elevators. The aft elevators move down to the interface and antenna construction level, whereas the forward elevators move down to energy conversion assembly substations. Other supplies would be moved directly to the appropriate area on level J.

The docked cargo pallets are moved (on its docking pad) to the unloading area, which is capable of storing 20 pallets. Mobile 40 meter MRWS cranes are located between each row of parked pallets; they are unloaded in the area onto the empty cargo pallets, are moved back to the docking area, where a tug docks to the top of the pallet. The tug lifts the empty pallet off the railroad docking pad and flies it back to the parked EOTV.

Figure 42 provides a detailed view of the level 'J' facilities and the logistic functional areas discussed below.

2.2.1 Cargo Docking/Unloading/Sorting Center

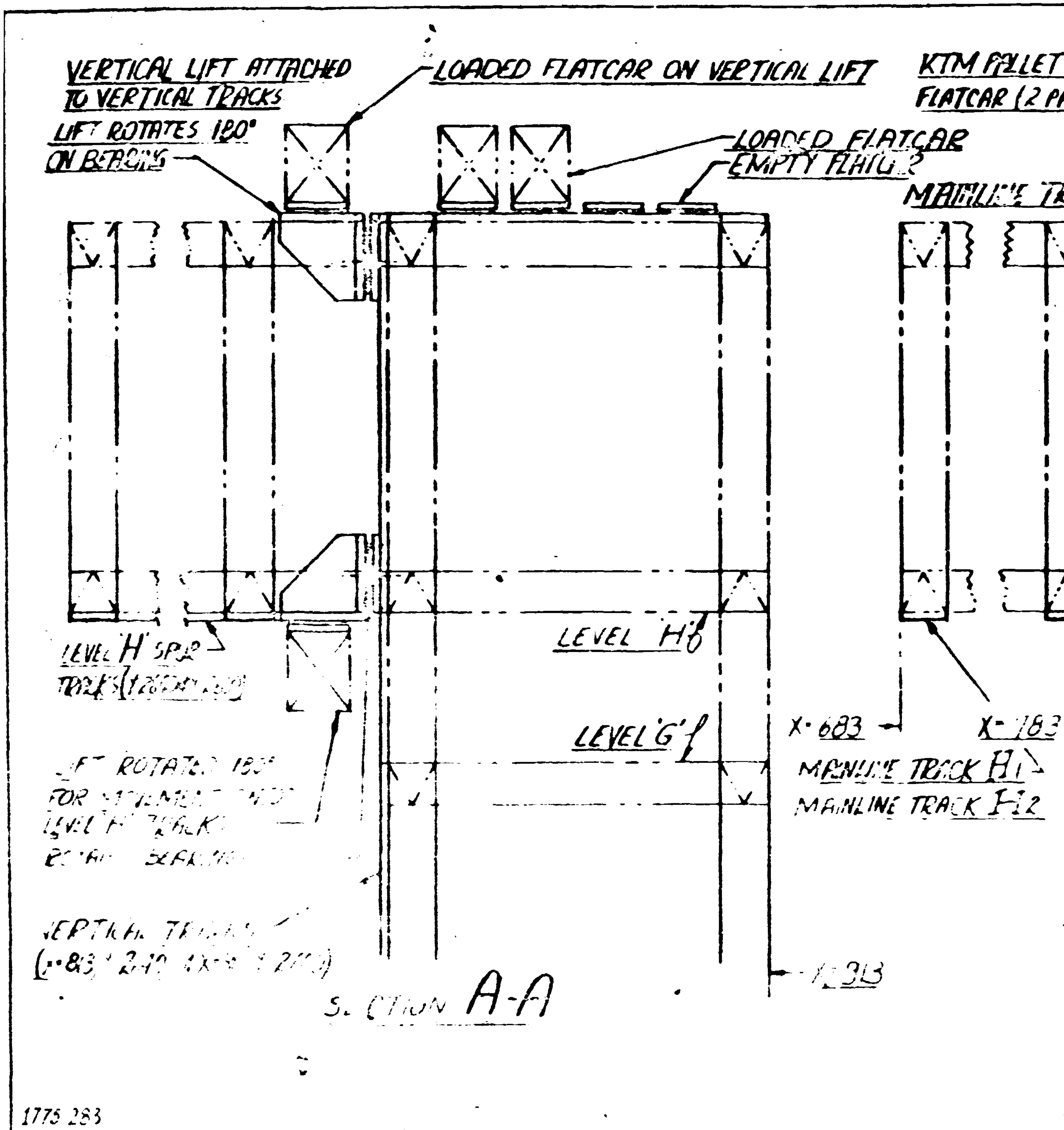
The cargo brought from LEO via the EOTV is delivered to this area for storage and processing. KTM pallets and cargo pallets are flown from the EOTV by cargo tugs. Special railed flatcars with docking mechanism are located in the docking center as shown in Figure 43. A four-man control center is located between the six docking pads. Two are configured to dock KTM pallets two for cargo pallets, one for a spare tug and the last one is a spare docking pad. After the KTM pallets are docked, they are unloaded with the 75 meter crane onto waiting railroad flat cars. From here they are moved to one of the three (3) staging areas for eventual delivery to antenna levels K and L. The cargo pallets remain on the docking pad and are railed to the unloading area. Five (5) rows (4 deep) provide storage for twenty (20) cargo pallets. Forty (40) meter MRWS cranes located between the rows of stored cargo pallets are used to unload the pallets onto waiting flatcars. These flatcars are moved either to one of the five (5) staging areas or to the sub-assembly factory. The loaded flatcars in the staging areas are eventually moved onto the vertical lift elevators for delivery to the lower construction levels.

The empty cargo pallets are moved back to the docking area. An unused tug docks to the cargo pallet and lifts it off level J base for return to the EOTV, station-keeping at least 1 Km away.

2.2.2 Cargo Staging & Distribution System

All material arriving from LEO is delivered to the cargo docking area. From there it is moved in its pallet to the unloading area. Dedicated MRWS cranes unload the cargo onto waiting flatcar transporters. Those pieces of hardware requiring buildup are moved into the subassembly factory. The sorted hardware and subassembled hardware are then moved to appropriate staging areas (5) and stored temporarily until required at the lower factory levels. The loaded flatcars are moved out onto one of the vertical lift elevators (16 shown) and lowered to the designated factory level. Figure 44 shows a loaded flatcar being delivered to Level "H". In this example, the railroad tracks are 180° to the Level "J" tracks. For this reason, the vertical lift elevator is mounted on a large rotary bearing. The whole loaded flatcar and elevator rotates 180° to put this unit into proper position with the Level "H" tracks. The loaded flatcar can now be moved onto the properly indexed tracks and proceed to designated area at this factory level. The same concept applies to the other lower levels of the factory.

Movement of material can be accomplished either on a railed track system or by a Free Flyer, as shown in Figure 45. During the construction of the SPS, large quantities of material have to be moved to pre-designated areas at regular time intervals. This type of operation fairly well dictates a semi-automated transportation system. It appears that the railed system can meet these requirements more readily than the Free Flyer system. The rail system depicted can move the people and material on the 'J' level quickly and efficiently. Once the material is processed through the unloading depot and subassembly factory, it then has to be moved down to the various construction levels. Three methods have been considered for interlevel transportation. The first requires a vertical rail system at each vertical stanchion The material in the horizontal flatcar has to be transferred into a waiting flatcar on the vertical track. This method is time-consuming and costly by virtue of additional track and flatcar requirements. The second method is a horizontal rail system on Level "J" supplemented with vertical elevators at each stanchion. In this scheme, the loaded flatcar is moved out to the waiting elevator platform. The elevator is lowered to the appropriate sublevel where the flatcar is either unloaded or side-railed. The third method is to provide an interconnected vertical and horizontal rail system. The two rail systems are connected by a curved track. In this manner one loaded flatcar can travel from point A to B. The second and third methods show promise for further study.



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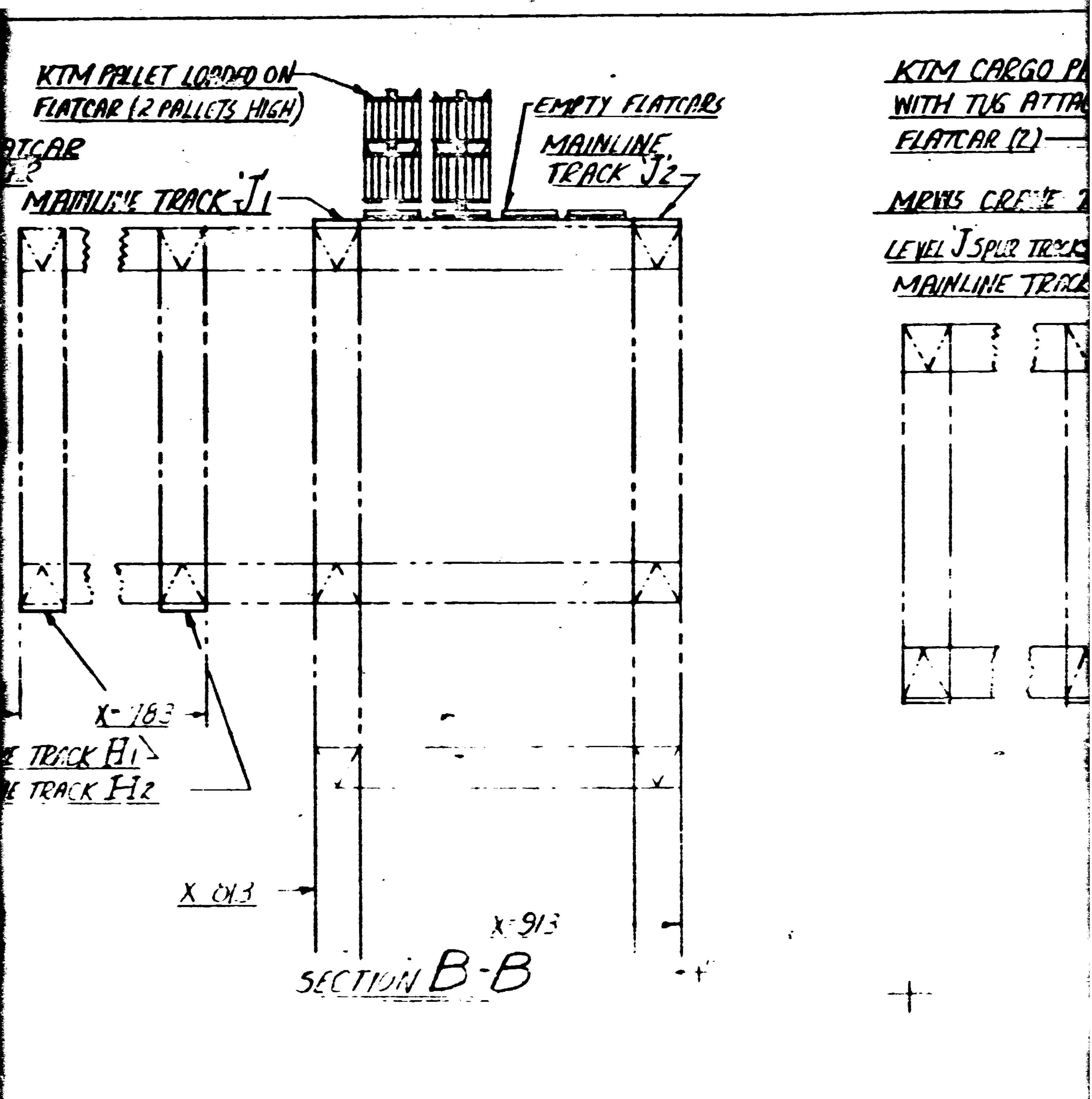

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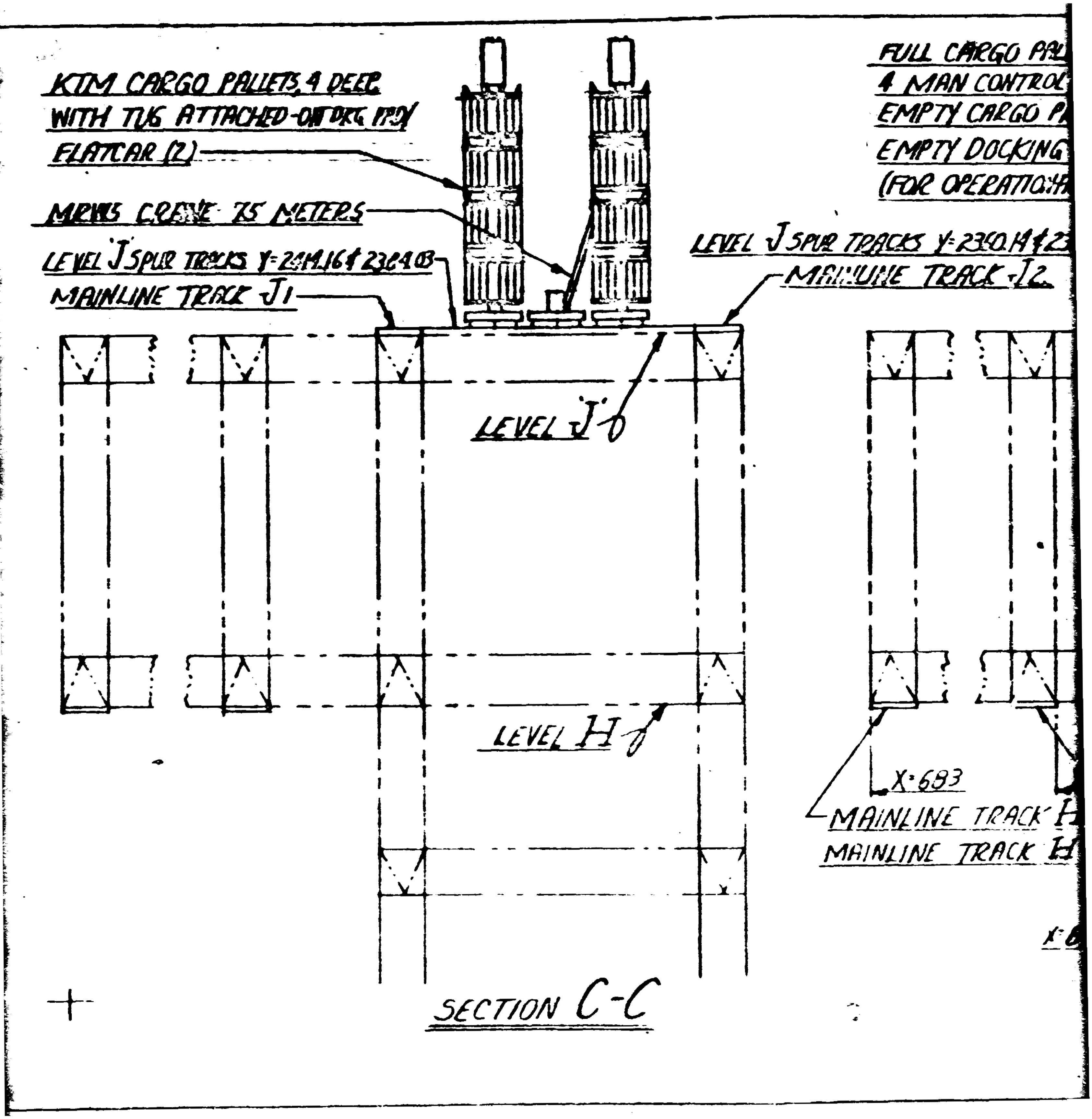

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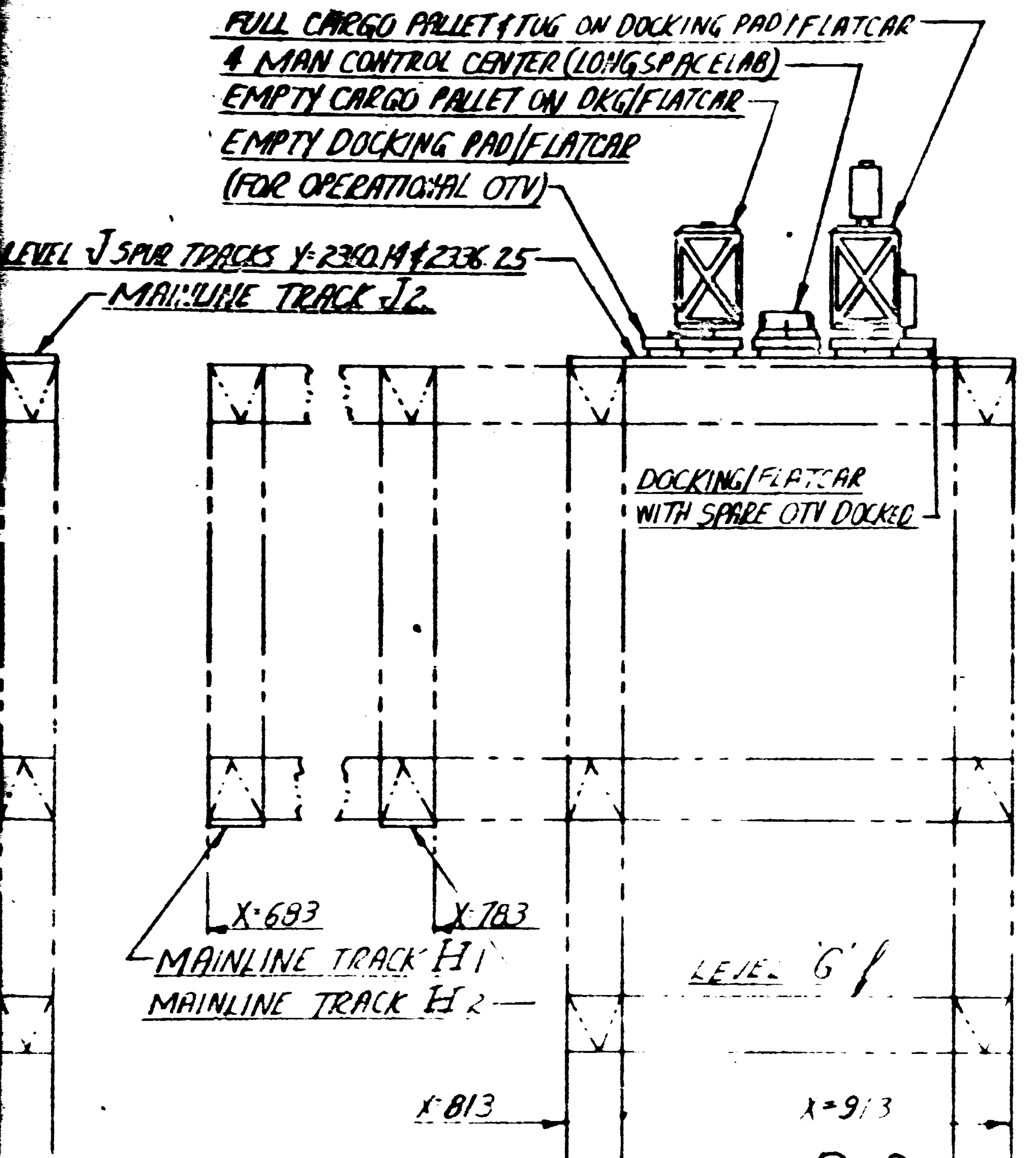
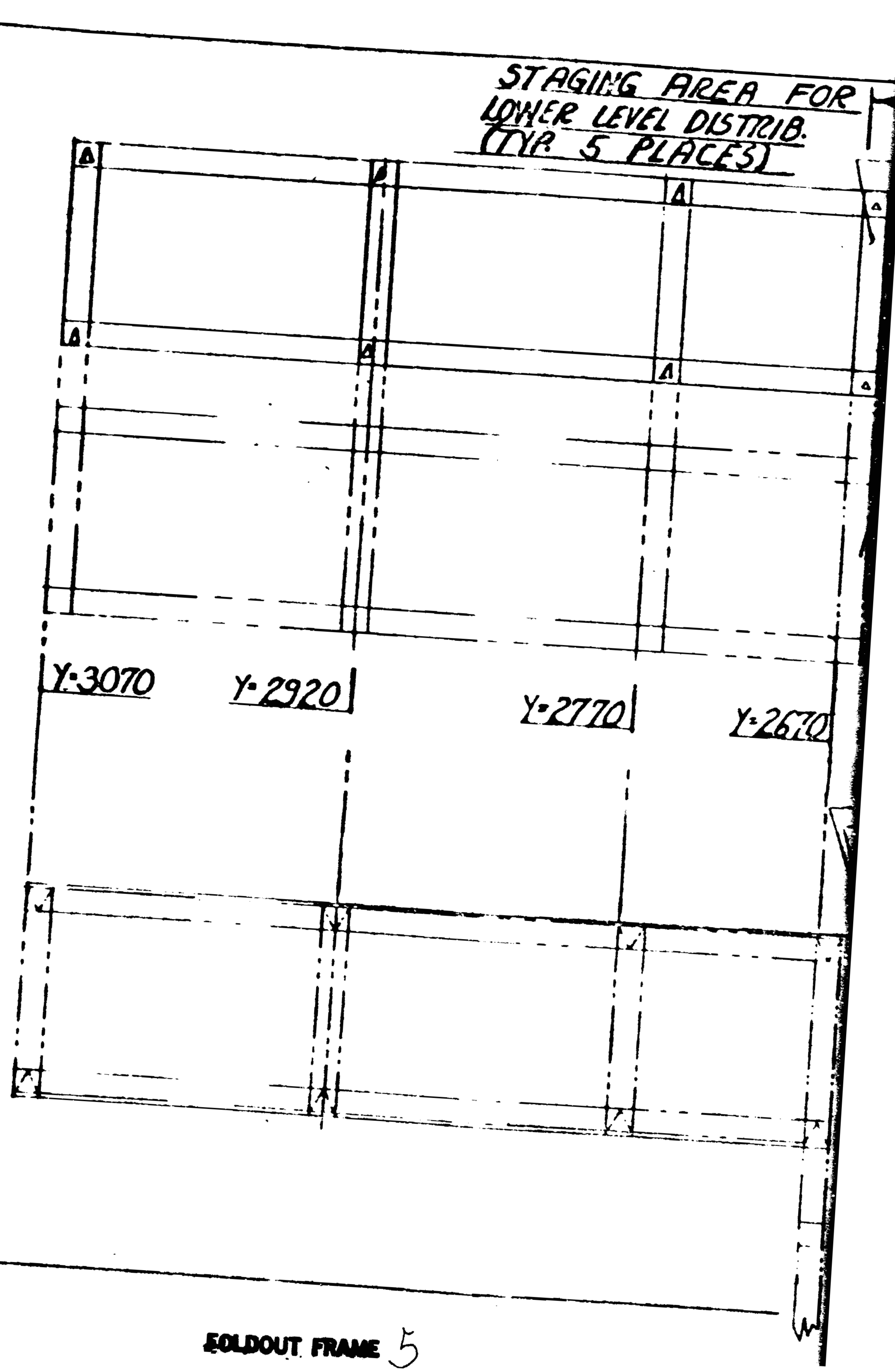

FULL CARGO PALLET & TUG ON DOCKING PAD/FLATCAR
4 MAN CONTROL CENTER (LONG SPACELAB)
EMPTY CARGO PALLET ON DKG/FLATCAR
EMPTY DOCKING PAD/FLATCAR
(FOR OPERATIONAL OTV)
LEVEL J SPUR TRACKS Y=2340.14 & 2336.25
MAINLINE TRACK J2
DOCKING/FLATCAR
WITH SPARE OTV DOCKED
X=683
X=783
MAINLINE TRACK H1
MAINLINE TRACK H2
LEVEL 'G'
X=813
X=913

SECTION D-D



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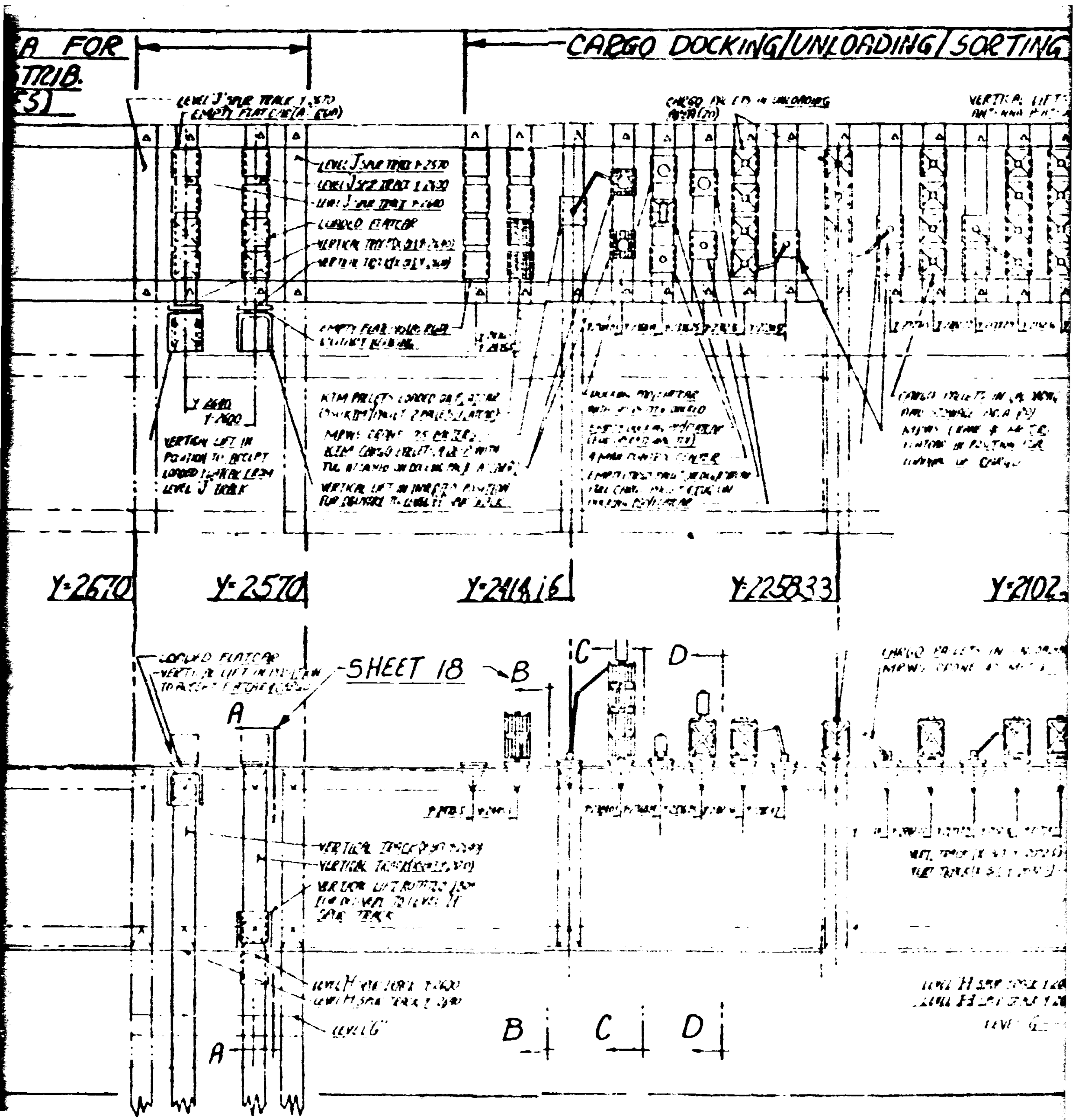

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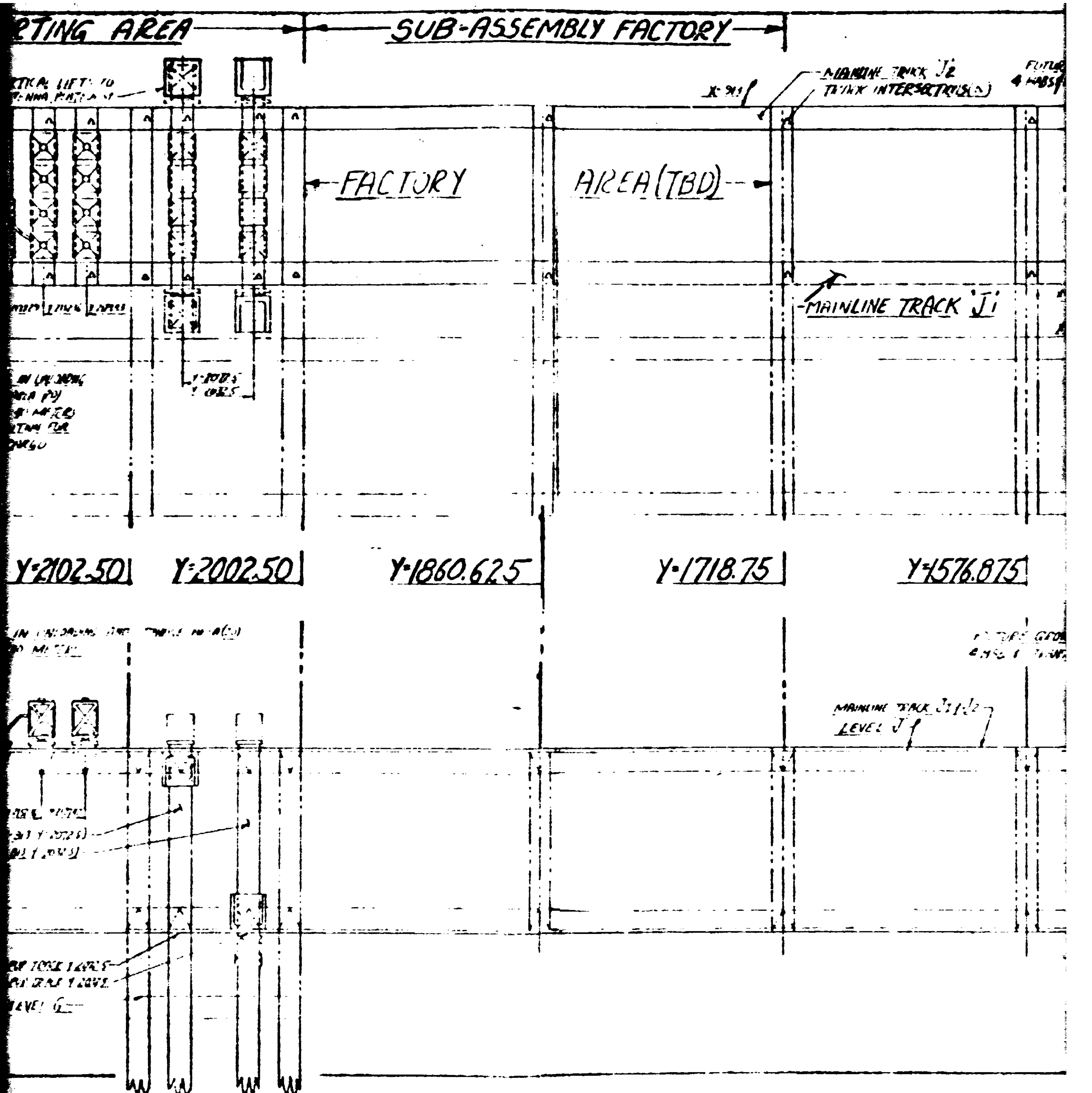

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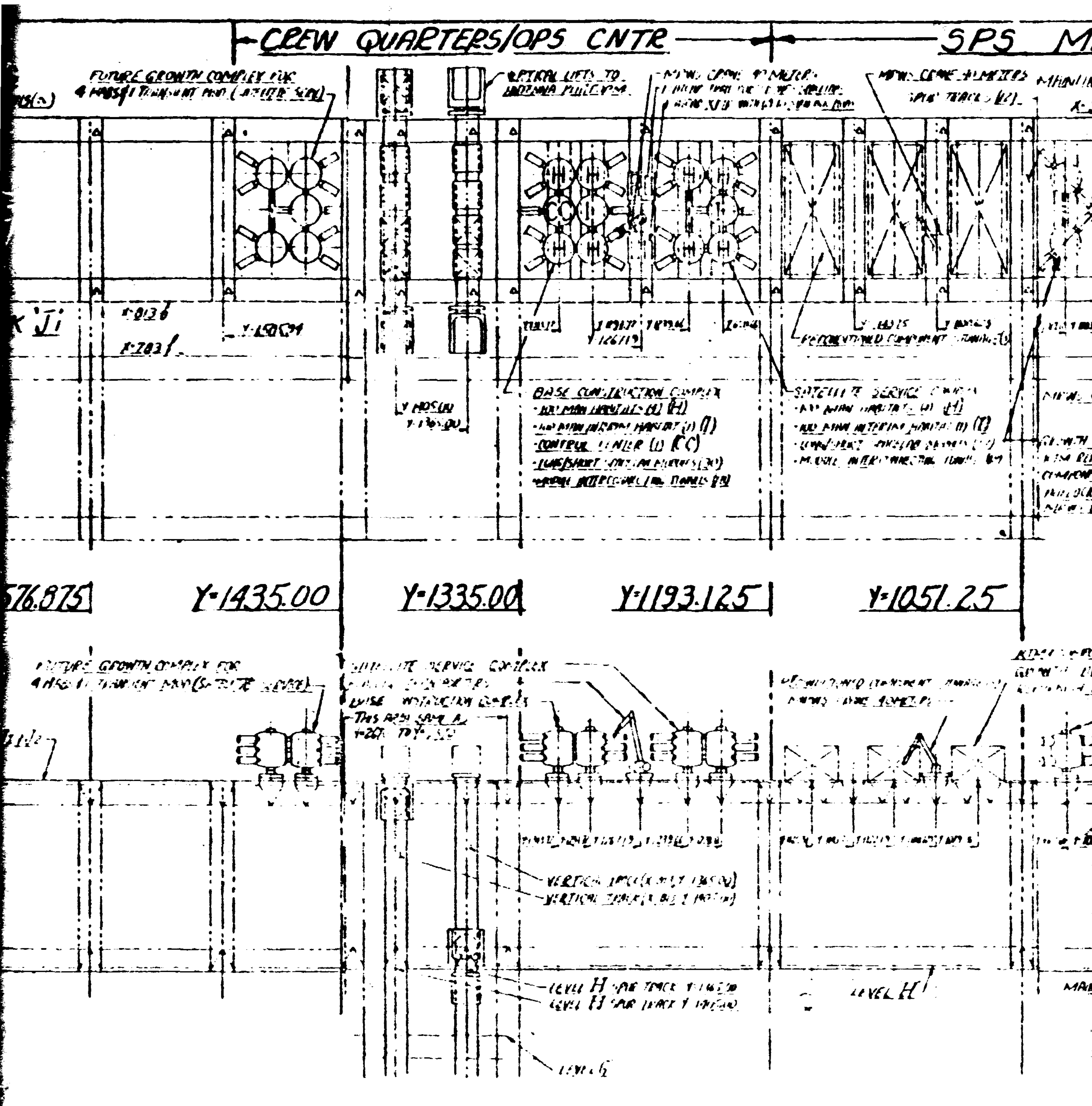
ITY



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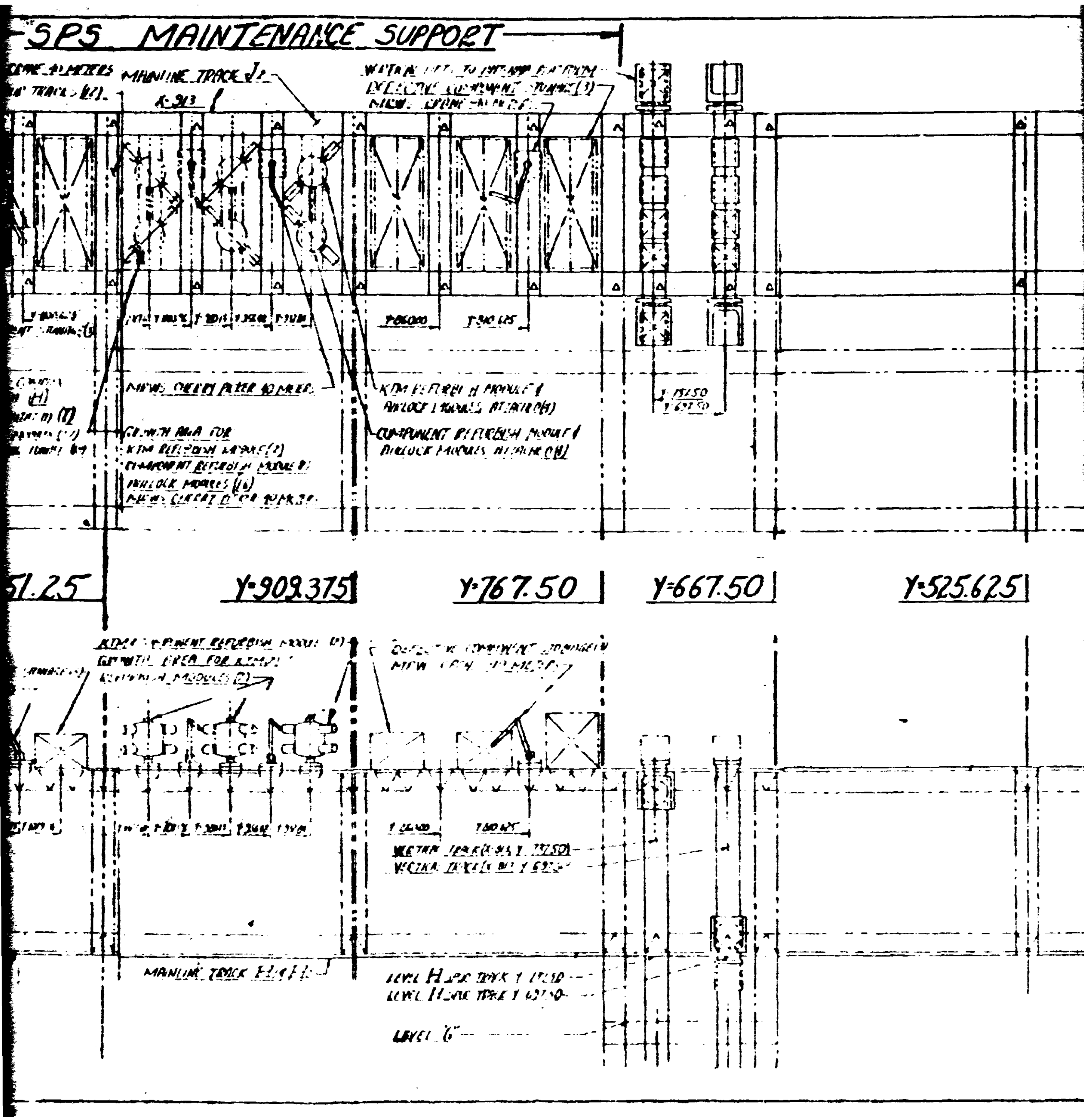

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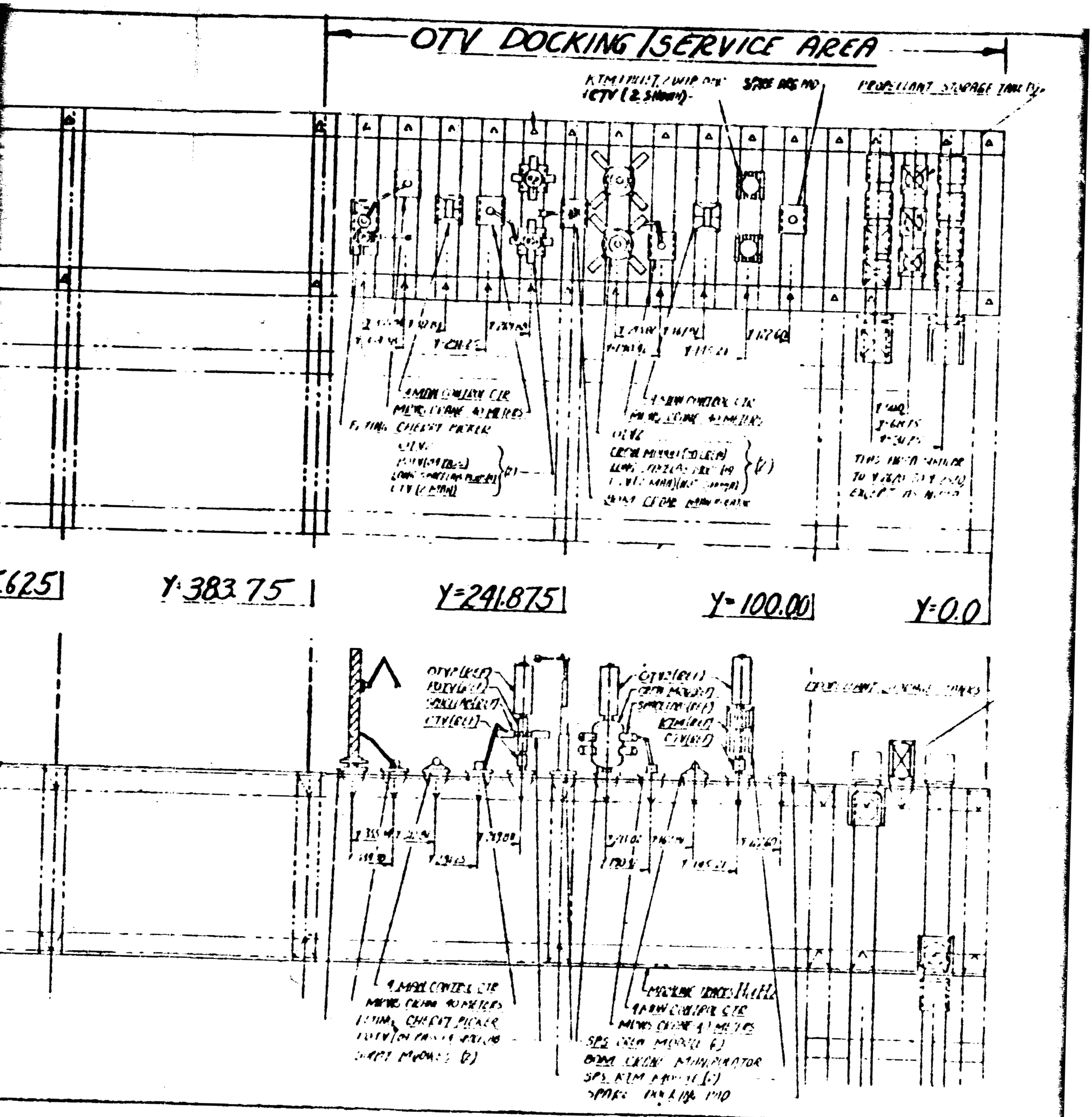
OTV DOCKING/SERVICE AREA
.625
Y=383.75
Y=241.875
Y=100.00
Y=0.0

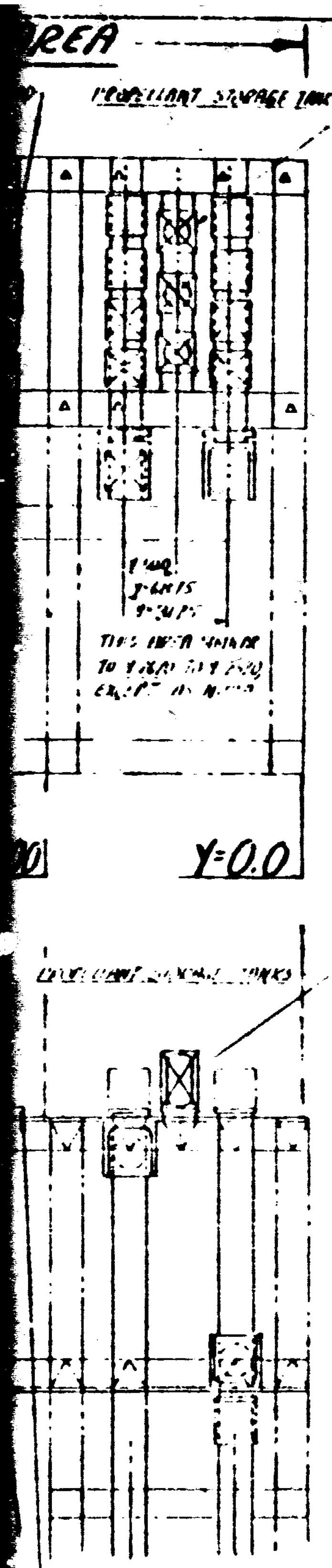

FIGURE 42
GEO CONSTRUCTION BASE
LEVEL J ARRANGEMENT
G.W HARMS 10/3/73

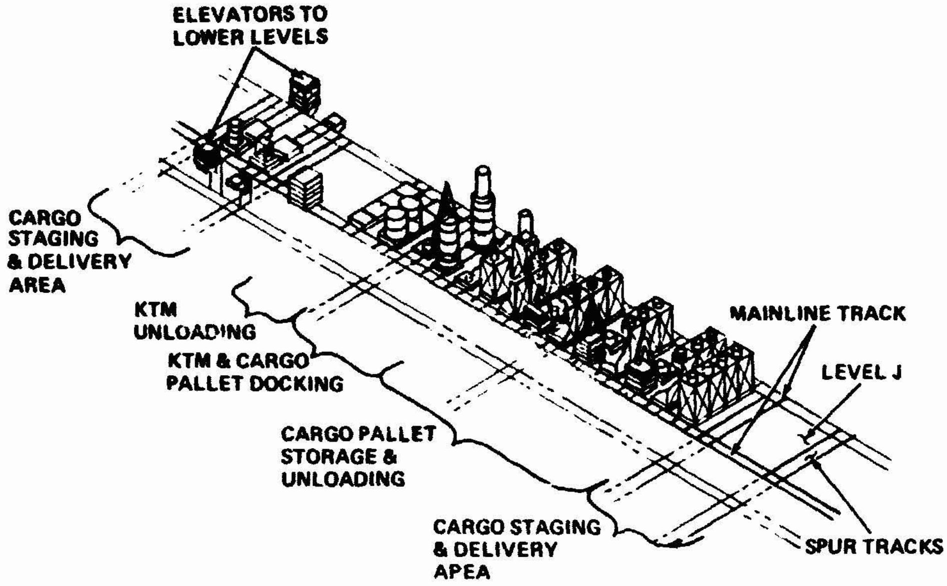

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Figure 43 Level "J" - Cargo Docking/Unloading/Sorting Center

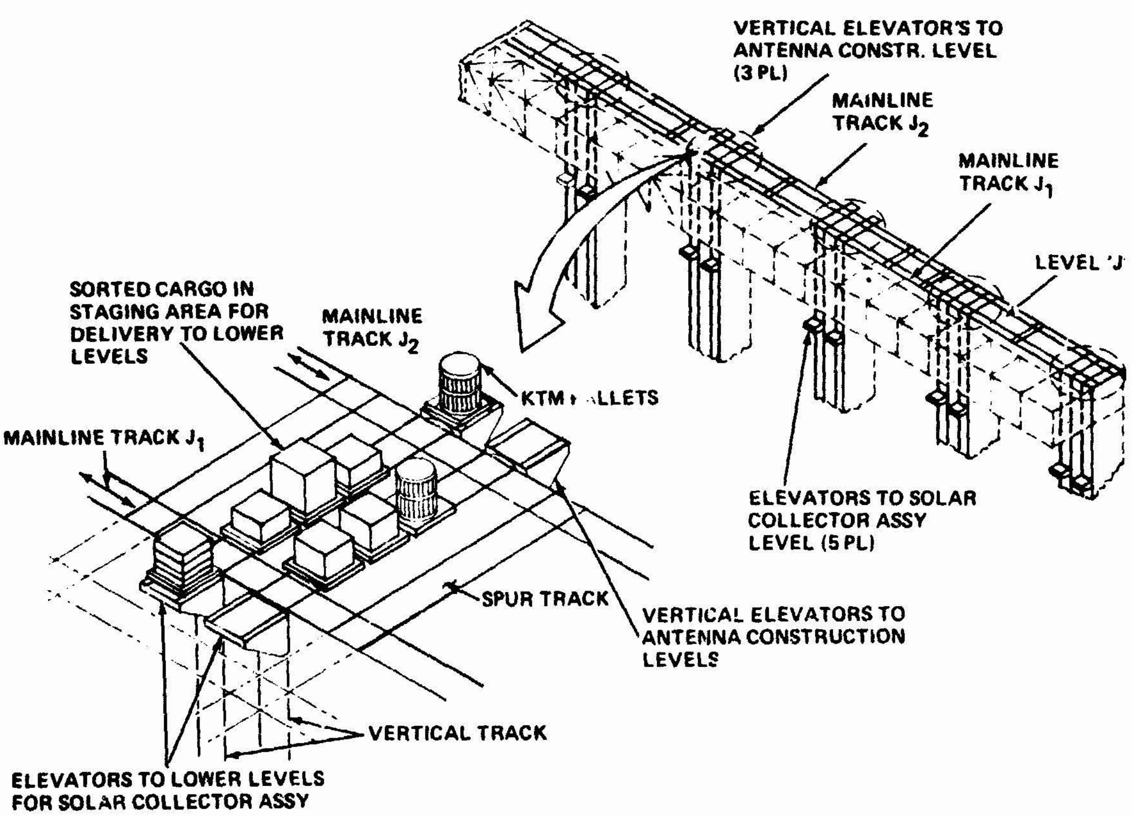

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Figure 44 Cargo Staging & Distribution System

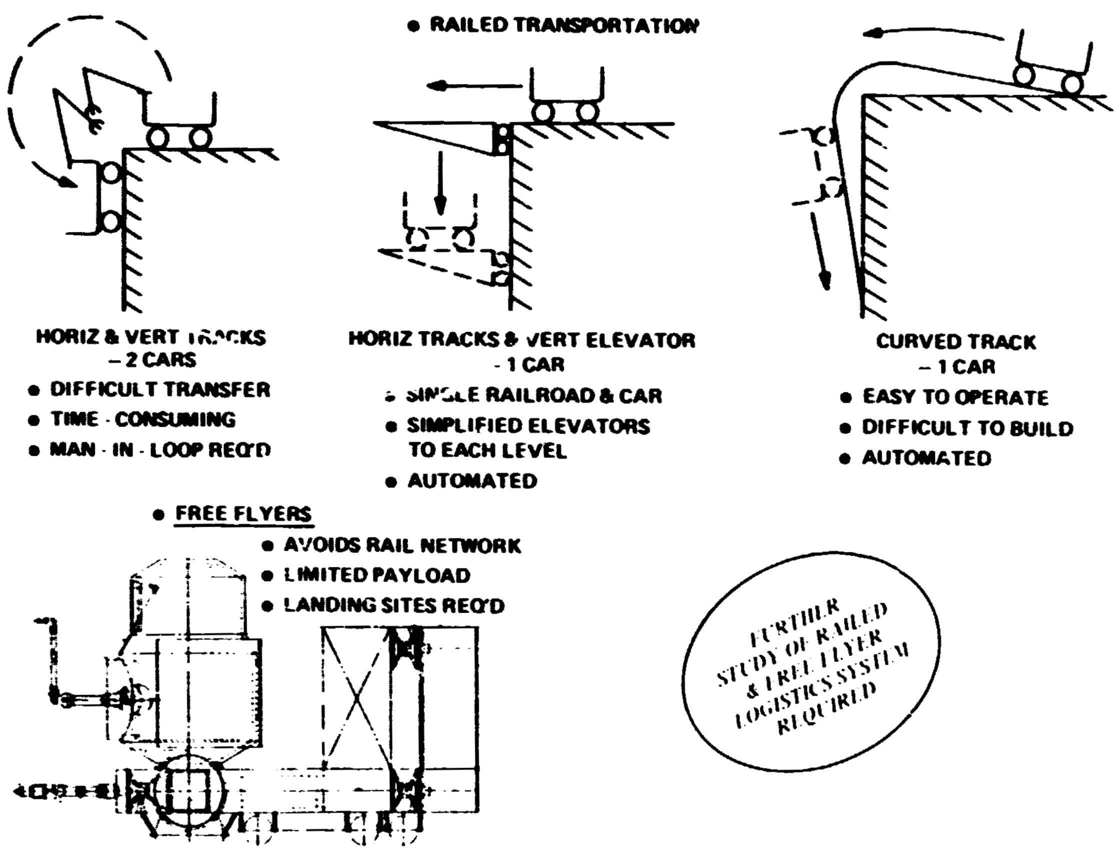

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Figure 45 Interlevel Material Transfer Options

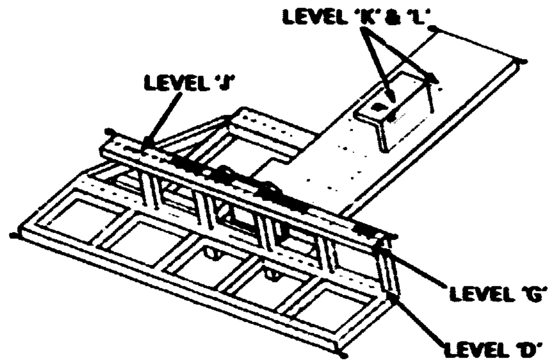
2.2.3 GEO Base Personnel Distribution and Transfer Concepts

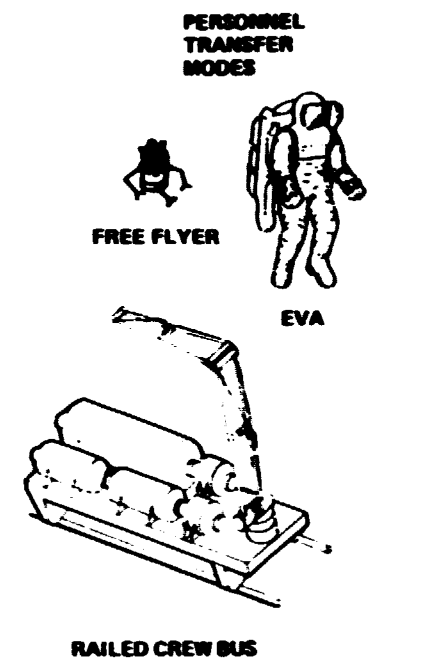
Figure 46 illustrates the distribution of personnel during a typical work shift. Approximately five (5) people are located in cherry pickers at Level D, working on structure assembly. Another eleven (11) people are located in various assembly devices at Level "G", working on structure and solar array assembly. Thirty (30) people are working on the antenna on levels "K" and "L" and are far away from the central home base. The remainder of the people are located throughout Level "J". Five hundred sixty-five (565) people are located in the eight (8) Habitats, either off duty or at work. Seventy-three (73) people are working in the Control Center, from which all facets of the GEO Base and SPS are controlled. The Refurbishment Modules house one hundred forty-three (143) people.

Personnel can move about the GEO Base in three different modes of transportation. Quick and direct movement can be accomplished using a MRWS type of free flyer. This vehicle can carry two people and limited hardware to almost any location on the Base or Satellite. The crew can work at the site, while in shirt sleeve attire inside the MRWS. Some work tasks will require that the crew get into close areas that are inaccessible by other means. In this EVA mode the crew member will don a GEO EMU and MMU and traverse short distances to the work site. For movement of personnel, a railed bus is used. The railed crew bus operates on the 12.7 meter track system, provided for movement of people and supplies. The bus shown is sized to move large numbers of people from the POTV to the Habitats, while another is sized to move a small amount to the various work stations each day. The Bus Transporters can reach the berthing ports on all modules, while moving on spur tracks between mainline J1 and J2 tracks.

2.2.4 Crew Quarters/Operations Center

The crew quarters and operations center, shown in Figure 47, contains all the pressurized modules for crew living and control of the base complex. Six large modules are grouped together in a geometric pattern and interconnected with tunnels. Four of these modules are used for habitats for four hundred (400) persons. Two modules (identical in size) are situated between these habitats, one is used as a base operations control center and the other is used as an interim habitat for one hundred (100) transients. Thirty (30) berthing points are located on these modules for attachment of spacelab modules, such as airlock, resupply, waste disposal, expendables, passenger delivery, and vehicle transfer. Since these modules are all interconnected,





LEVEL 'J' ACTIVITY	PEOPLE/SHIFT
HABITATS & CONTROL CENTER	585
WORK AREAS	73
REFURBISHMENT MODULES	143
LEVEL 'K' & 'L' ACTIVITY	
• ANTENNA FACILITY	30
LEVEL 'G' ACTIVITY	
• ENERGY CONVER. ASSY	11
LEVEL 'D' ACTIVITY	
• COLLECTOR ASSY	5
TOTAL	827

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Figure 46 GEO Base Personnel Distribution & Transfer Concepts

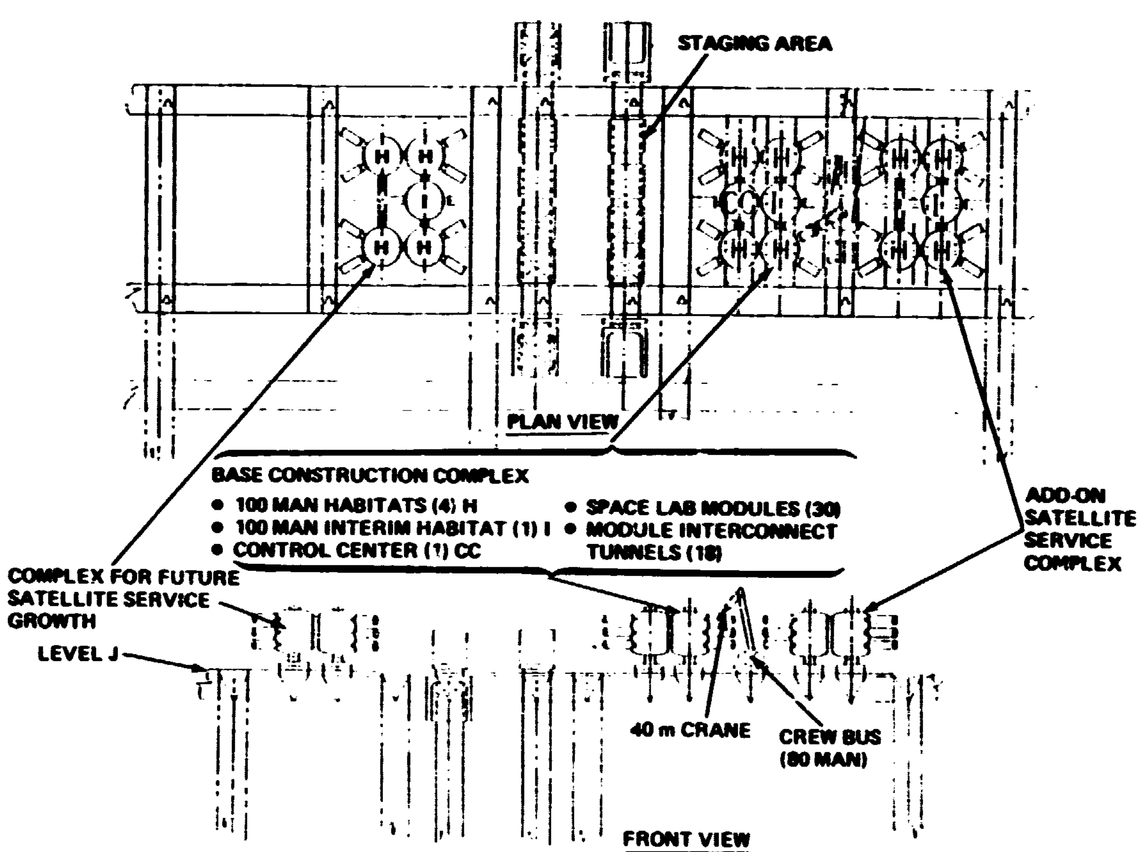

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Figure 47 Crew Quarters & Operation Center

transfer between modules can be accomplished in shirt sleeve attire. This grouping is used to house the personnel that are required to work and control the operations of the base construction complex.

Adjacent to this aforementioned complex, but not connected to it, is another grouping of large modules. These five modules are used to house up to four hundred (400) people and one hundred (100) transients, required to maintain and service twenty (20) satellites. Again, the modules are interconnected with tunnels and also have berthing ports for attachment of twenty-seven (27) spacelab modules.

An additional area has been established for the installation of five (5) more large modules. They are configured the same as the five (5) previously mentioned. This complex is added at some future date when forty (40) satellites are being serviced. When sixty (60) satellites are serviced, the first group of habitats is no longer needed for base construction and can be used to house the additional personnel. There is ample room to even add another new complex and abandon the first group of habitats, if desired.

The habitat complexes are all bordered with spur line railroad tracks. In this manner operation buses with supplies and people can be interchanged with the 40 meter MRWS crane on the bus transporter.

2.2.5 OTV Docking and SPS Maintenance Support

The OTV docking/service area has been located at the end of the base, because of the high level of flight activity. Numerous flights to and from level 'J' dictate that its location be in one corner of the complex, so its operation will not affect normal movement for base construction. Sixteen (16) spur line railroad tracks are placed between the mainline 'J'1 and 'J'2 tracks to enhance traffic flow.

A docking pad is provided for the flying cherry picker, as shown in Figure 48. A 40 meter MRWS crane located on an adjacent track services this unit. Two (2) docking pads are provided for the POTVs arriving from the LEO Base. Each POTV is sized to deliver 84 people with four (4) spacelab modules attached. These vehicles are serviced with a 80 meter crane, a 40 meter MRWS crane and a bus transporter. A four (4) man control center is located between the complex of landing pads.

The other half of this complex contains five more docking pads, two (2) for SPS OTVs, two (2) for KTM pallets and one (1) spare. The SPS OTVs contain a crew module for eighty (80) people, a two (2) man control transfer vehicle and eight

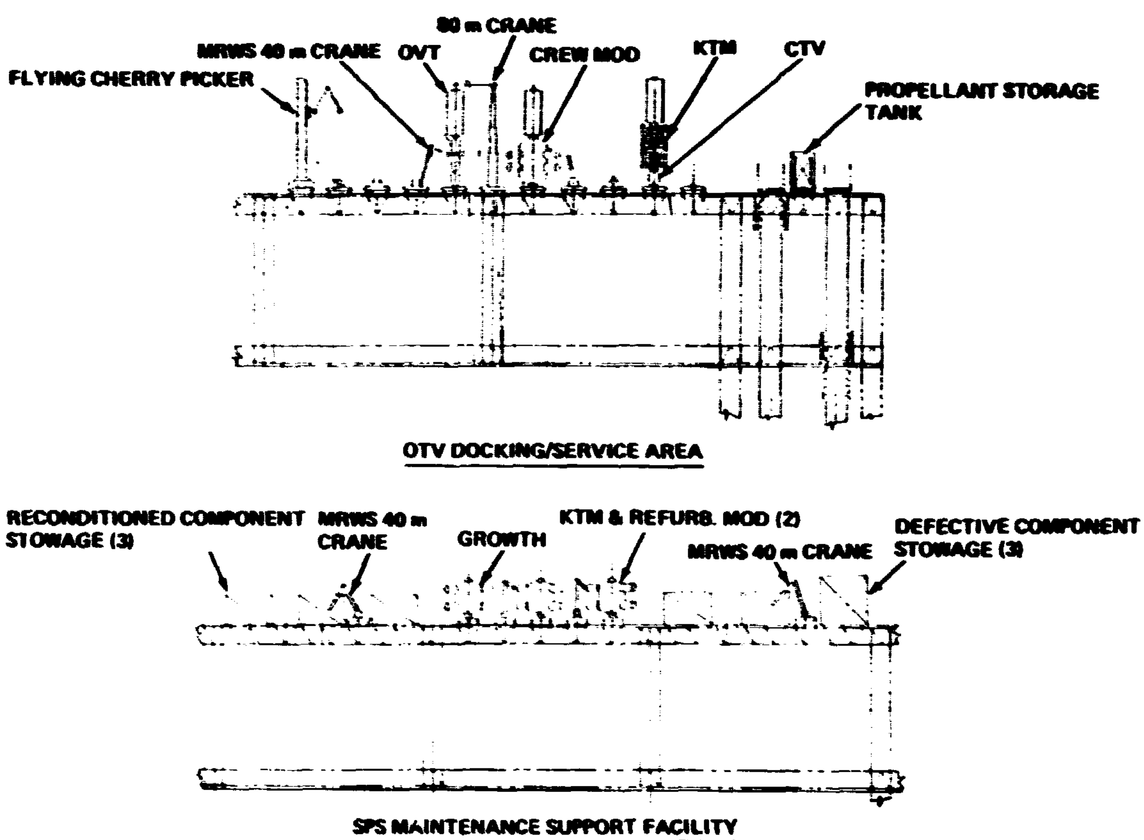

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Figure 48 OTV Docking & SPS Maintenance Support

(8) long spacelab modules filled with supplies for the thirty (30) day mission to service the operational satellites. The KTM vehicles are sized to return defective klystron assemblies to the refurbishment module. Reworked assemblies are loaded onto this vehicle by one of the railed cranes in the area. A second control center is located between this grouping of landing pads. Three (3) propellent storage tanks are provided at the corner of the Level 'J' complex.

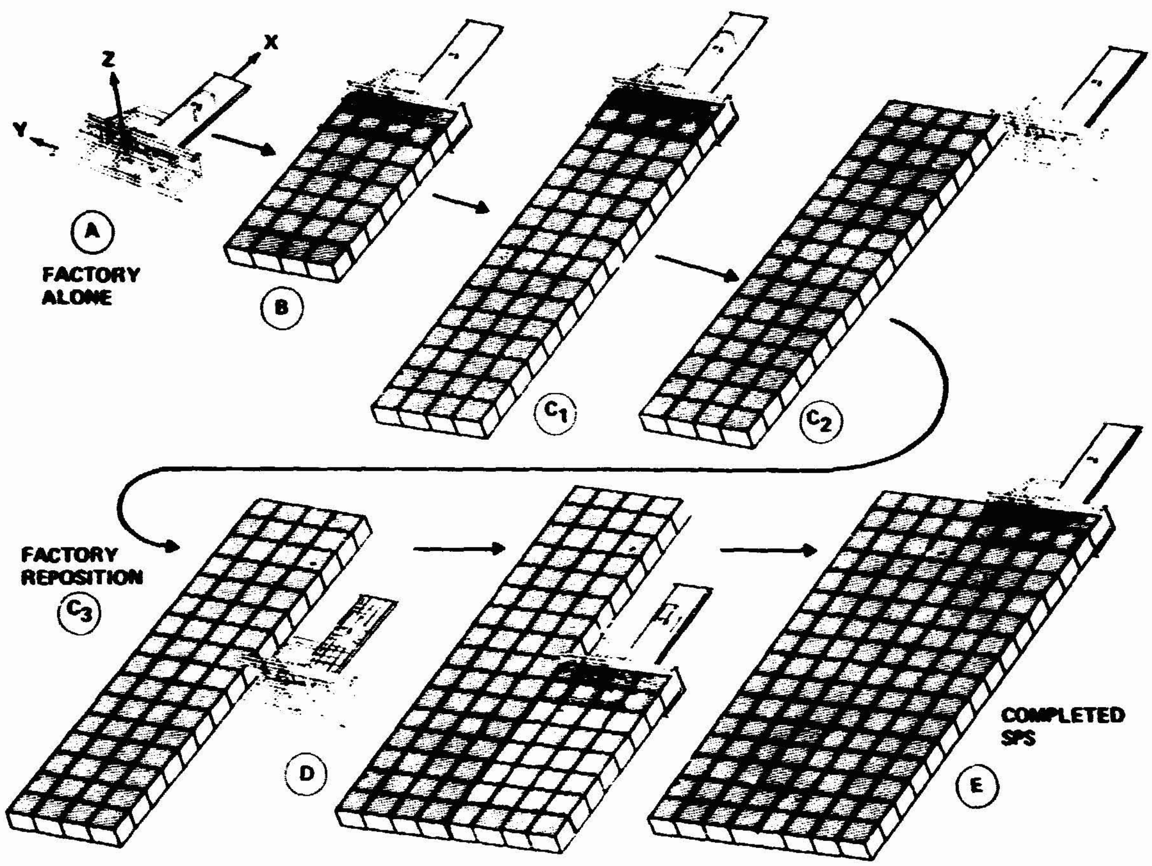
The SPS Maintenance Support Facility is adjacent to the OTV docking area and the Crew Quarters/Operations Center. The defective material, brought back from the operational satellites, is off loaded onto railroad flat cars and transported over to the defective component storage area. When scheduled, this material is moved into the KTM and component refurbishment modules, where they are reconditioned. The reworked hardware is placed in the reconditioned component stowage area, for eventual return to the OTV docking area.

2.3 BASE ATTITUDE AND STATIONKEEPING CONTROL

During the 6 month construction cycle, the GEO base will undergo a significant increase in mass and/or a significant shift in center of pressure and center of gravity, as shown in Figure 49. Hence, the flight attitude selected for the GEO base is impacted by SPS construction requirements and the orbital mechanics environment.

Figure 50 lists the major requirements that must be considered when selecting the GEO base/satellite construction attitude. Only two of the nine requirements listed appear to be significant when selecting the most desirable orbital attitude for the GEO Base. These are sun angle and EOTV unloading locations, which are discussed further below.

Previous SPS studies by Grumman for ECON have shown that the propulsion system penalty for attitude control in GEO is small. The structural loading due to mass offset during construction appears lower than baseline design limits. Since maneuver capability is required for the base, SPS operational attitude and orbitkeeping do not affect construction attitude. Base stability for docking presents no problem since the GEO orbital rate is low. Location of communication antennas does not constrain attitude, as they can easily be located on the base open structure once other attitude requirements are imposed.



1775-214W Figure 49 SPS Construction Phases

- BASE ATTITUDE CONTROL (GRAVITY & SOLAR PRESS TORQUE)
- √ SUN ANGLE – CONSTRUCTION LIGHTING
  - – SPS SOLAR ARRAY DEPLOYMENT
  - – BASE SOLAR ARRAY
- SPS OPERATIONAL ATTITUDE
- BASE MANEUVERS TO NEXT CONSTRUCTION SITE
- BASE STABILITY FOR DOCKING
- √ EOTV UNLOADING LOCATION
- COMMUNICATION ANTENNA LOCATION
- STRUCTURAL LOADING
- ORBITKEEPING

1775-215W Figure 50 Base Satellite Construction Attitude Requirements

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2.3.1 Candidate GEO Construction Attitudes

If the SPS solar arrays are deployed in sunlight, high voltage is generated as the solar arrays are exposed to sunlight. Shorting cables could be used to terminate the solar array output, however, the method of handling these and the safety issues involved require study. Another approach to solving the problem is to orient the active side of the solar array away from the sun. This issue also affects maintenance on an operational SPS.

Two GEO base construction attitudes, shown in Figure 51, can provide the off-sun attitude during construction and then revert to on-sun attitude for final checkout and separation. The SPS solar arrays can be positioned with its longitudinal axis perpendicular to the orbit plane (POP), as the operational SPS, or be positioned in an earth pointed mode. Both attitudes minimize light impingement during construction and rely on longitudinal roll maneuvers to acquire on-sun conditions. Other variations of the two attitudes shown do not appear to offer any advantage.

2.3.2 Sun Illumination on Base/SPS

The direction of sun illumination affects crew visibility during daily operations and placement of solar arrays on the Base.

The crew should not face the sun during construction or docking operations. Over-the-shoulder illumination is best. Construction operations require at least 2 MW of electrical power. Fixed solar arrays are less complicated than gimbal type.

The left-hand illustration in Figure 52 shows the Base/SPS inertial reference to sun, simplifying the selected location of fixed solar arrays, docking approach and construction illumination constraints. The right-hand illustration shows a more complex illumination situation as the sunlight direction varies on the gravity-reference Base/SPS. These factors are pertinent to the selection of the GEO Base construction attitude.

2.3.3 EOTV Cargo Unloading Considerations

EOTV cargo unloading and transfer to the GEO base occurs while the 1.5 Km X 1 Km inertially oriented EOTV stationkeeps 1 Km away.

The EOTV location as it stationkeeps with the Base affects the flight path of Cargo Tugs (CT) as they unload the EOTV, the distance the CTs must travel to docking ports, and EOTV stationkeeping propulsion requirements. If the EOTV is not in the same orbital path as the GEO base then propulsion requirements are increased.

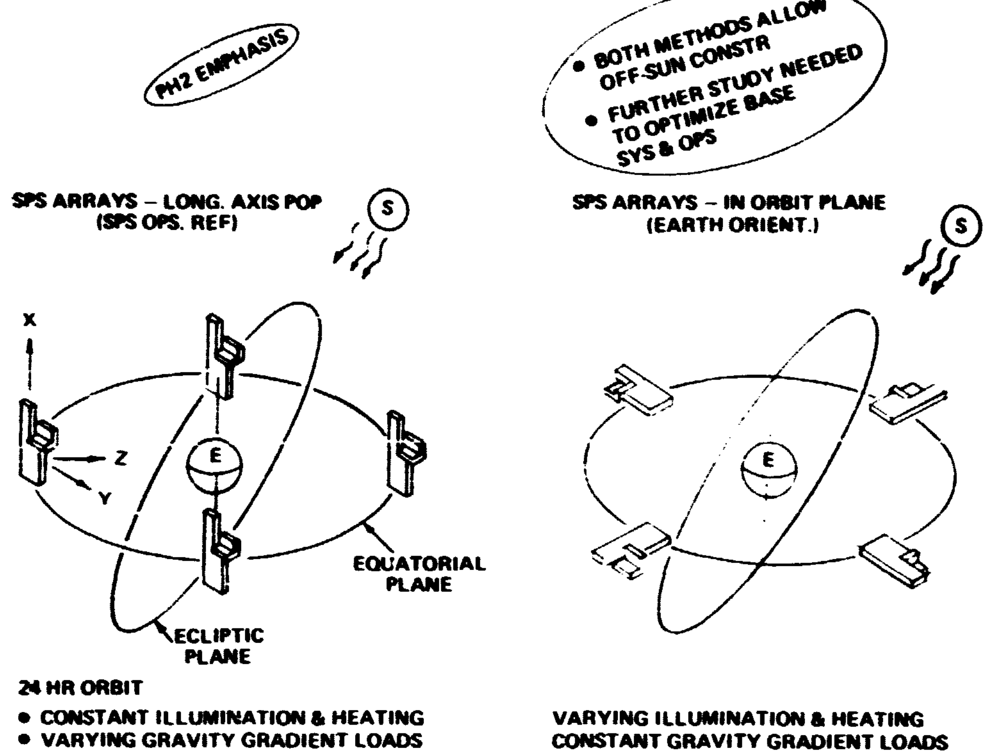

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Figure 51 Candidate GEO Base/SPS Construction Attitudes

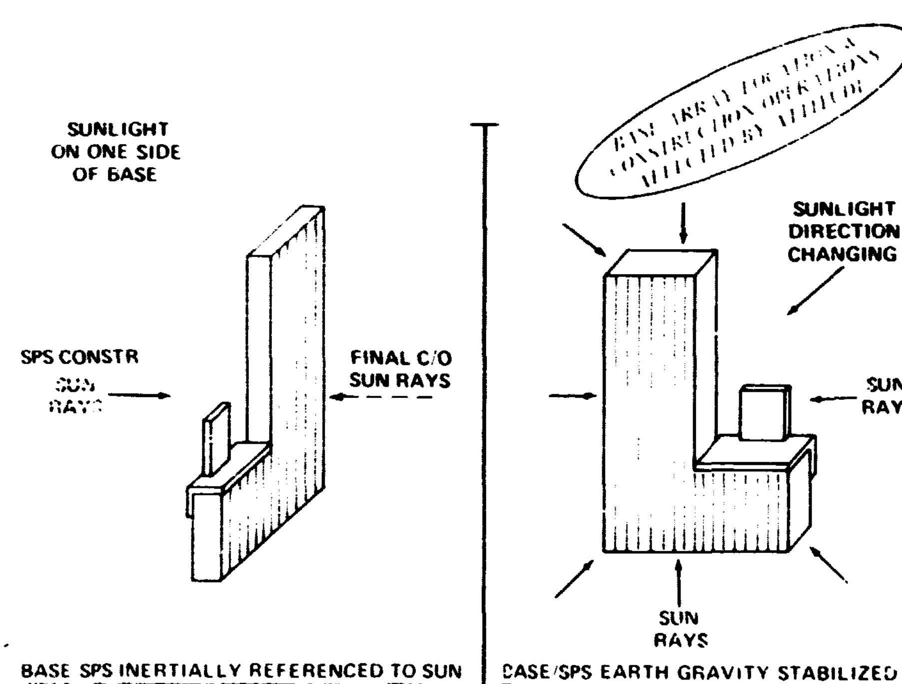

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Figure 52 Sun Illumination on Base/SPS

Ideally, the EOTV should be located alongside of the dock ports at minimum distance consistent with safety requirements. Attitude requirements of the Base and EOTV and orbital mechanics may dictate a changing relationship between these two vehicles in GEO orbit and separation distances greater than 1 km (baseline).

The baseline operational attitude for the SPS is a candidate for construction operations. The illustration in Figure 53 shows this attitude with the EOTV stationkeeping during a 24 hour period. Both spacecraft, are in the same orbital path with their solar arrays perpendicular to the sun. Note that the change in relative attitudes of the two vehicles during an orbit makes it appear that the EOTV is circling the Base/SPS. If this is the operating condition, then the two vehicles are separated by approximately 4 km at times and the CT flight paths are continually changing - an obvious impact on CT propulsion and control requirements. One solution is to maneuver between the two vehicles only when they are in the most favorable geometric location.

If the Base is earth gravity stabilized as shown, then the relative location of the Base and the EOTV remains fixed. The EOTV, however, rotates 360° every 24 hours with respect to the Base. Hence, CT flight paths will also be constrained to the most favorable geometric arrangement.

2.3.4 GEO Base Flight Control Requirements

Figure 54 lists the basic requirements for the GEO base flight control system. The POP mode was emphasized for the SPS off-sun solar array construction requirements during the Phase 2 effort, since previous SPS feasibility studies show low propellant requirements for all GEO flight attitudes. The POP attitude permits base solar arrays to be fixed on the structure and also allows construction operations to be conducted under constant lighting and solar heating conditions. Further study is recommended on other flight attitudes, including the impact on base logistic operations, satellite construction constraints and base power design penalties.

The major environmental disturbances considered in the Phase 2 analysis of attitude control and stationkeeping functions are also listed in Figure 54.

2.3.5 SPS Construction-Attitude Control and Stationkeeping Analysis

A preliminary analysis was performed to establish the attitude control and stationkeeping systems required during SPS construction in geostationary orbit. The procedure used to develop a control system concept entailed the following:

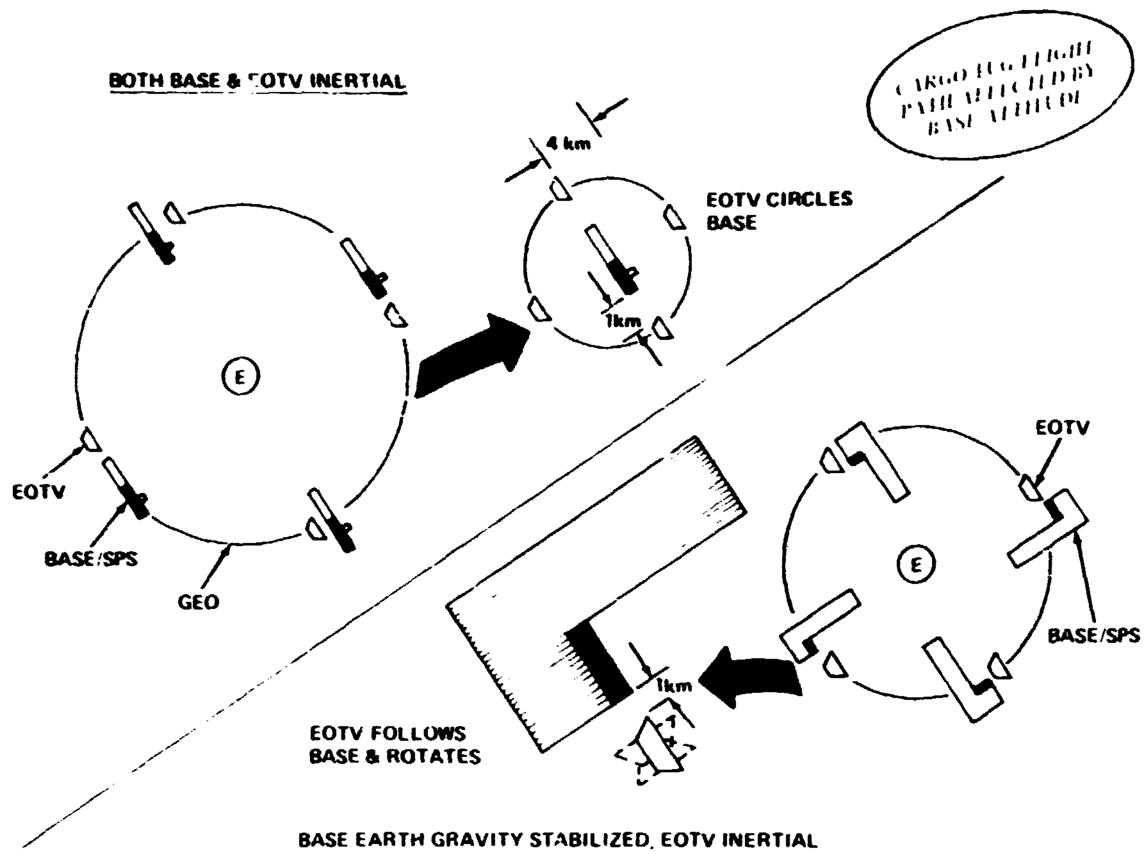

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Figure 53 EOTV Cargo Unloading Considerations

REQUIREMENTS

- CONSTRUCT SPS ARRAYS OFF-SUN (POP)
- FINAL SPS C/O IN POP ATTITUDE (ON-SUN)
- MAINTAIN SPS/BASE AT DESIRED ORBITAL POSITION WITHIN ± 1
- SEPARATE SPS/BASE AT DESIRED GEO LONGITUDE (I.E. 90°W TO 150°W)
- TRANSFER BASE TO NEXT ORBITAL CONSTRUCTION SITE (~ 10)
- PROVIDE BASE ONLY THRUSTER CONTROL

ENVIRONMENTAL DISTURBANCES

- ATTITUDE CONTROL FORCES
  - GRAVITY GRADIENT
  - SOLAR PRESSURE
- STATIONKEEPING FORCES
  - SUN & MOON GRAVITATIONAL INFLUENCE
  - SOLAR PRESSURE
  - ELLIPTICITY OF EARTH EQUATORIAL PLANE

1775-219W

Figure 54 GEO Base Flight Control Requirements & Environmental Disturbances

- Estimate effects of environmental disturbances during SPS construction
- Select control actuators and recommend configuration
- Estimate propellant consumption.

2.3.5.1 Control System Analysis - Figure 51 identifies the spacecraft body axis system and the orbital orientation, which was studied. The vehicle is assumed to be in a Perpendicular-to-Orbit-Plane (POP) mode with the X axis perpendicular to the orbit plane, the Y axis in the orbit plane, and the Z axis oriented to face in the general direction of the sun at all times.

The major groundrules and assumptions for the purposes of performing the analysis are summarized in Figure 55.

Seven significant construction phases in the build-up scenario for the SPS have been identified and were previously shown in Figure 49. Each configuration has been chosen to represent a significant increase in mass and/or a significant shift between the center of pressure and center of gravity of the configurations. The assumed body axis system is also identified on the first configuration.

The mass properties of the end builder combined with the SPS during each of the construction phases are summarized in Figure 56. A seven fold increase in weight with wide variations in center of gravity and moments of inertia characterizes the construction cycle.

Figure 57 presents a plot of the weight growth in terms of five mission phases. The duration of each mission phase is identified along with the configurations previously identified which apply during each phase. Phase C is conservatively described by configuration #4, (or C2), which occurs prior to factory translation and (approximately) after translation as fabrication of the second half begins. Configuration #3 is similar to #4 but with less severe requirements and #5 is a short-term transition configuration.

The gravity gradient torque disturbances acting on the spacecraft are basically cyclic with a zero bias level. Disturbances about the X axis act at twice orbital rate with the peak value being a function of the difference between the I_{YY} and I_{ZZ} inertias. Disturbances about the Y and Z axes act at orbital rate and are a function of the I_{XZ} and I_{XY} cross product terms. The peak values of the torque disturbance levels, and the corresponding momentum developed during each orbit to counter the gravity gradient torque disturbances for each of the configurations previously identified are presented in Figure 58.

- GEO CONSTRUCTION OF ONE SPS IN 6 MOS.
- POP ORIENTATION/SPS ARRAYS FACED AWAY FROM SUN DURING CONSTRUCTION
- CONSTRUCTION CYCLE WILL END WITH SPS AT DESIRED ORBITAL POSITION
- ΔV TO REPOSITION FACTORY ONLY AT BEGINNING OF CONSTRUCTION CYCLE
- RESUPPLY EOTV WILL PROVIDE RENDEZVOUS
- COMMONALITY WITH SPS AND/OR EOTV DESIRED

1775-220W

Figure 55 Ground Rules & Assumptions

CONFIG	WEIGHT $KG \times 10^3$	CG, METERS X	Y	Z	MOMENTS OF INERTIA, $KG\text{-}M^2 \times 10^9$ Ixx	Iyy	Izz	Ixy	Ixz	Iyz
1	8,360	1120	35	440	2,900	5,010	5,150	-170	-710	-180
2	20,500	-400	15	180	9,000	115,405	120,640	70	4,860	-105
3	32,650	-2265	10	115	14,865	572,670	583,250	810	11,710	-85
4	32,650	-2265	1325	115	59,390	570,560	627,775	-131,900	11,720	-4,915
5	32,650	710	1325	115	59,300	204,125	259,230	-2,480	805	-4,915
6	44,790	125	965	80	80,630	322,515	398,620	-5,257	2,945	-3,600
7	56,930	-2760	760	65	95,200	1,029,980	1,120,500	-110,425	13,540	-2,840

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Figure 56 Mass Properties — 4 Bay End Builder & SPS

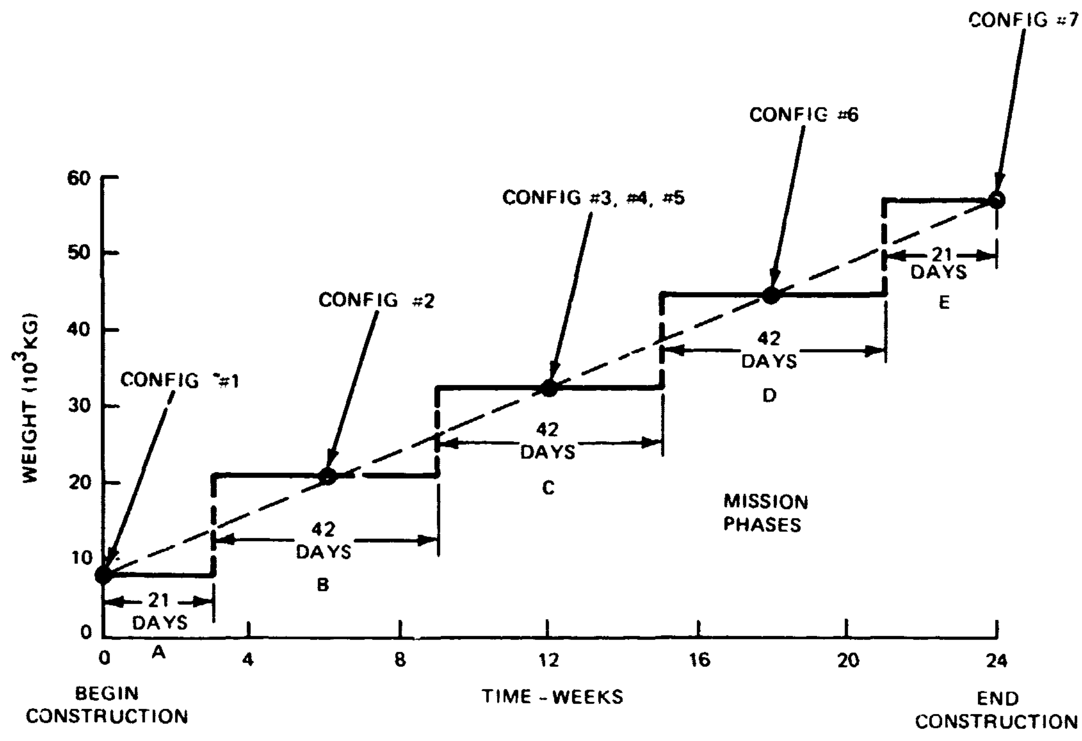

Figure 57 Mission Phase Development

CONFIG.	(I_{ZZ}-I_{YY}) 10^9 KgM^2	PEAK GRAV. GRAD. TORQUES - 10^3 NM			MOMENTUM STORAGE PER ORBIT - 10^8 NMS		
		X AXIS	Y AXIS	Z AXIS	X AXIS	Y AXIS	Z AXIS
1	140	1.1	11.3	2.7	.2	3.1	.7
2	5235	41.6	77.3	4.3	5.7	21.2	1.2
3	10580	84.1	186.	12.9	11.6	51.2	3.5
4	57215	455.	186.	2100.	62.5	51.2	576.
5	55105	438.	12.8	29.4	60.2	3.5	10.8
6	76105	605.	46.8	83.9	83.1	12.9	23.
7	90520	720.	215.	1760.	98.8	59.	482.

1775-223W

Figure 58 Peak Gravity Gradient Torque Disturbances & Momentum Storage Requirements

Disturbance torques that result from solar pressure acting on the satellite are basically steady state disturbances during any given orbit. The level of this disturbance is a funciton of the surface characteristic, its cross-sectional area, and the distance between the center of pressure and the center of gravity. The level of these torques and the momentum build-up during each orbit caiculated for each assumed configuration are presented in Figure 59. The corresponding configuration geometry changes during each mission phase along with location of the center of gravity, which was used to calculate solar pressure torques are shown in Figure 60.

Figure 61 presents the combined effect of the gravity and solar disturbances. It shows the peak torque disturbance levels and identifies the dominant source(s). It also identifies the accumulated momentum per orbit (or per day) for both disturbances.

Two sets of thruster locations were considered for this study, as illustrated in Figure 62. The "factory-only thrusters" are assumed to be in six fixed locations through-out the mission. They provide the primary three-axis attitude control during the entire build-up phase of the SPS. These thrusters never change position on the construction base. The "optimized thrusters" on the other hand will be relocated in four different locations depending on the configuration. The assumed location of the optimized thrusters during the build-up are shown as circles in the figure.

Two thruster concepts were considered: the double-gimbal SPS thruster panel, which operates with an I_{SP} of 20,000 seconds and the similar but larger EOTV thruster panel with an I_{SP} of 8,000 seconds. Attitude control propellant requirements are shown in Figures 63 and 64 for the optimized and factory-only thrusters locations, respectively, and two different I_{SP} levels. The factory-only thruster concept results in an increase of approximately 76% over the optimized thruster concept.

Figure 65 and 66 present the thruster characteristics of the SPS and EOTV gimbailed thruster panels, respectively. The available contral torques for each axis, as a function of mission phase, are also presented. Comparison of these torque levels with the requirements of Figure 61 indicate that the lower thrust SPS panels do not provide sufficient control torque in certain cases (circled). The EOTV thruster, however, provides satisfactory control torque for all mission phases for both the optimized and factory-only thruster configurations.

The EOTV thrusters in the factory-only configuration are the recommended concept for SPS construction. They provide satisfactory control authority and lower input power levels. The selection process also considered difficult logistic problems

CONFIG.	PEAK SOLAR PRESSURE TORQUE 10^3 N-M			MOMENTUM STORAGE PER ORBIT 10^8 N-M-SEC		
	Tx	Ty	Tz	Hx	Hy	Hz
1	0	4.5	0	0	3.89	0
2	35.1	113.7	7.7	30.3	98.3	6.7
3	35.1	403	18.6	30.3	348	16.1
4	134	366	18.6	116	316	16.1
5	164	28.1	18.6	142	24.2	16.1
6	134	172	140	116	149	121
7	351	674	41.8	303	582	36.1

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Figure 59 Solar Pressure Disturbance Summary

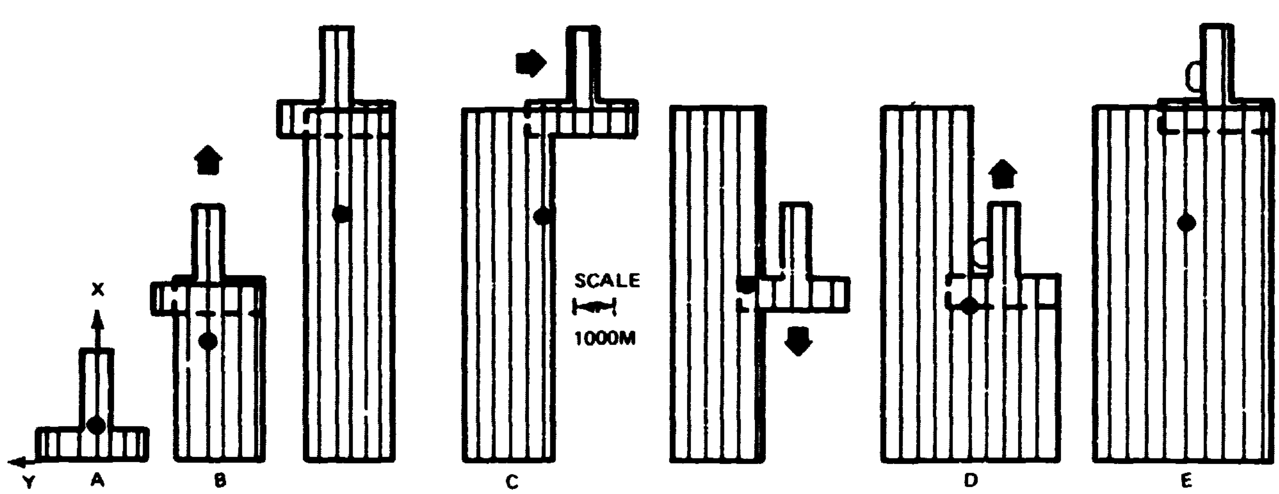

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Figure 60 Configuration Changes During Construction

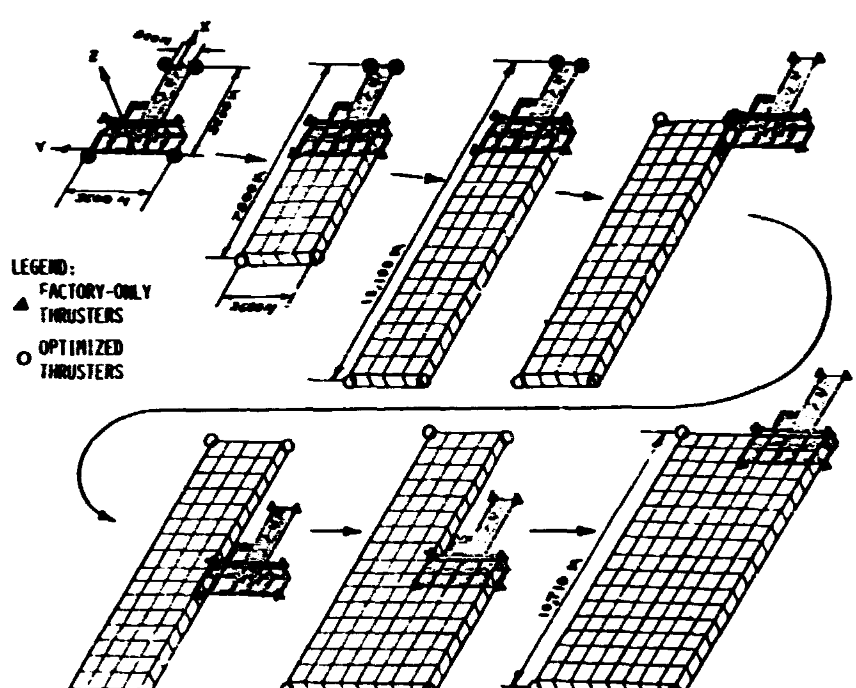
MISSION PHASE	CONFIG	TORQUE 10^3 N-m Tx	Ty	Tz	MOMENTUM PER ORBIT 10^8 N-M-SEC Hx	Hy	Hz	
A	1	1.11 GG	15.8 GG/S	2.70 GG	.153 GG	3.89 S	.742 GG	21 DAYS
B	2	76.7 GG/S	155.3 GG/S	12.0 GG/S	36.0 GG/S	120. S	7.9 S	42 DAYS
C	3	119. GG/S	589. GG/S	31.5 GG/S	41.9 S	399. S	19.6 S	42 DAYS*
	4	589. GG	552. GG/S	2120. GG	179. GG/S	367. S	592. GG	
	5	602. GG/S	40.9 GG/S	48.0 GG/S	202. GG/S	27.7 S	26.9 GG/S	
D	6	739. GG	219. S	224. S	199. GG/S	162. S	144. S	42 DAYS
E	7	1070. GG	889. S	1800. GG	402. GG/S	641. S	518. GG	21 DAYS
								168 DAYS TOTAL

LEGEND:
- GG — GRAV GRAD PRIMARY SOURCE
- S — SOLAR PRESSURE PRIMARY SOURCE
- GG/S — COMPARABLE GRAV GRAD & SOLAR

*CONFIGURATION 4 REQUIREMENTS ARE USED TO CONSERVATIVELY CHARACTERIZE MISSION PHASE C FOR PROPELLANT CALCULATIONS.

1775-226W

Figure 61 Peak Torque & Momentum Requirements



1775-227W

Figure 62 Thruster Arrangement Options

MISSION PHASE	MOMENT ARMS (M)			PROPELLANT*PER AXIS (KG)			TOTAL PROPELLANT PER PHASE (KG)	
	Lx	Ly	Lz	X	Y	Z	Isp=20,000 SEC	Isp=8,000 SEC
A	3600	3600	3600	0.4	11.6	2.	14.	35.
B	2680	7800	7800	288.	330.	22.	640.	1600.
C	2680	10710	10710	1430.	735.	1185.	3350.	8380.
D	5380	10710	10710	794.	1358.	290.	2442.	6105.
E	5380	10710	10710	804.	641.	519.	1964.	4910.
						TOTAL	8410.	21030.

* Isp = 20,000 SEC

1775-228W

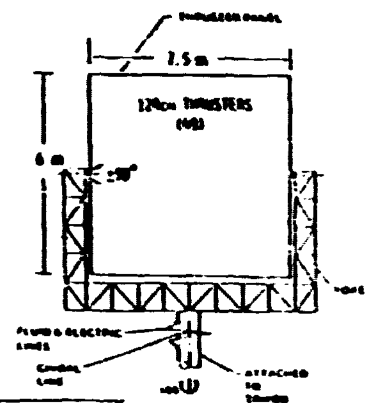
Figure 63 Propellant Requirements (Optimized Thruster Locations)

MISSION PHASE	MOMENT ARMS (M)			PROPELLANT*PER AXIS (KG)			TOTAL PROPELLANT PER PHASE (KG)	
	Lx	Ly	Lz	X	Y	Z	Isp=20,000 SEC	Isp=8,000 SEC
A	3600	3600	3600	0.4	11.6	2.	14.	35.
B				30.	714.	46.	790.	1975.
C				1067.	2184.	3524.	6775.	16940.
D				1184.	966.	857.	3007.	7520.
E	3600	3600	3600	1197.	1907.	1121.	4225.	10560.
						TOTAL	14811.	37030.

* Isp = 20,000 SEC

1775-229W

Figure 64 Propellant Requirements (Factory-Only Thruster Locations)



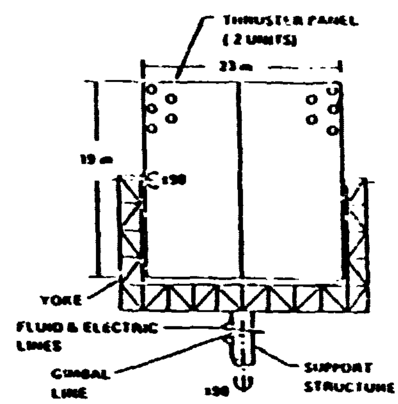
SPS GIMBALLED THRUSTER PANELS

- 25 120 CM ION THRUSTERS
- 150 N THRUST PER PANEL
- 6 N THRUST PER THRUSTER
- Isp = 20,000 SEC
- ARGON PROPELLANT
- 7.5 MEGAWATTS INPUT POWER PER PANEL

MISSION PHASE	OPTIMIZED CONTROL TORQUE (10^3 N-m) X	Y	Z	FACTORY-ONLY CONTROL TORQUE (10^3 N-m) X	Y	Z
A	540.	1080.	1080.	540.	1080.	1080.
B	402.	2340	2340.			
C	804.	3215.	3215.			
D	804.	3215.	3215.			
E	804	3215.	3215.	540.	1080.	1080

1775-230W

Figure 65 Control Torque Capability With SPS Thruster Panels



EOTV GIMBALLED THRUSTER PANELS

- 289 120 CM ION THRUSTERS
- 838 N THRUST PER PANEL
- 2.9 N THRUST PER THRUSTER
- Isp = 8,000 SEC
- ARGON PROPELLANT
- 3.6 MEGAWATTS INPUT POWER PER PANEL

MISSION PHASE	OPTIMIZED CONTROL TORQUE (10^3N-m) X	Y	Z	FACTORY-ONLY CONTROL TORQUE (10^3N-m) X	Y	Z
A	3020	6035	6035	3020	6035	6035
B	2245	13075	13075			
C	4490	21955	17950			
D	4490	21955	17950			
E	4490	21955	17950	3020	6035	6035

1775-231W

Figure 66 Control Torque Capability With EOTV Thruster Panels

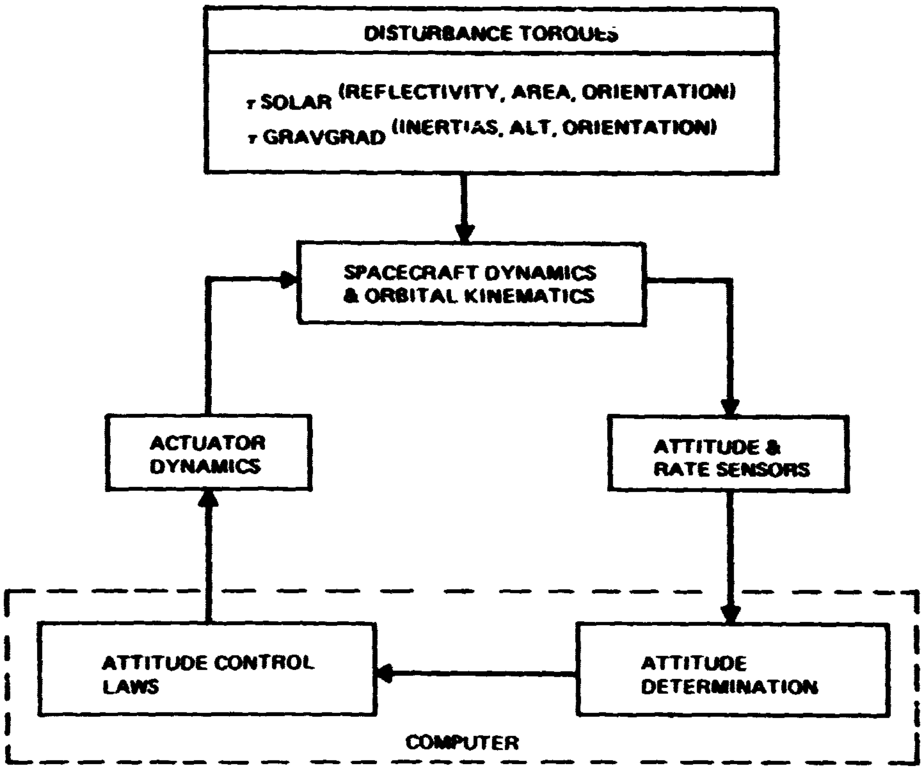
associated with providing operable thrusters on the SPS structure for the optimized configuration which requires thrusters in temporary locations without available SPS solar array power. The corresponding propellant requirement for this recommended concept is 37,030 Kilograms, as seen in Figure 64. The system block diagram is illustrated in Figure 57.

2.3.5.2 Stationkeeping Analysis - During the satellite construction phase, a series of complex flight operations are being performed, which may require the construction base to maintain a degree of stationkeeping with respect to a specific location over earth. Included in these operations are EOTV cargo delivery flights, originating from a depot in LEO and bringing raw materials used for satellite construction, to an orbiting position near the construction base in GEO. A near continuous flow of manned tug flights are then used to shuttle cargo from the co-orbiting EOTV to the construction base.

The operations may dictate that the free flying EOTV and construction base maintain position control with respect to each other. They may also require that the combined GEO complex maintain control with respect to a specified region over earth to simplify operations with the LEO Depot. In addition, operations performed in placing the constructed satellite in it's operational orbit slot may pose similar requirements on construction base location. Consequently, an analysis was performed to determine the extent of orbital drift occurring on the construction base during the construction phase. The orbital perturbations considered to be a significant influence on GEO base station keeping requirements are discussed below

- Sun and Moon Gravitational Effects - The gravitation influence of the sun and moon cause a gradual plane change to a geosynchronous orbit relative to the ecliptic. Because the desired orbit's equatorial plane is fixed relative to the ecliptic, the regression of this orbit takes on the form of an inclination drift relative to earth-centered coordinates. The total period of the regression from nominal to the maximum inclination of 15° is 53 years.

  Figure 68 shows the magnitude of the plane change which occurs and the ΔV requirements needed to restore the orbit to nominal. The out-of-plane motion is undesirable to both the construction base and the constructed satellite since this motion is to be nulled, when moving the satellite to its geosychronous orbit slot.



1775-232W

Figure 67 Attitude Control System Elements

SUN & MOON GRAVITATIONAL EFFECTS

- CAUSES ORBITAL PLANE CHANGE OF ≈0 .86° PER YEAR
- REQUIRES A $\Delta V \approx 150$ FT/SEC PER YEAR TO NEGATE OUT-OF-PLANE DRIFT. (72 FT/SEC PER 170 DAY CONSTRUCTION PERIOD)

RECOMMENDED PROCEDURES

- PRE-SET ORBIT PLANE TO -.4° AT START OF CONSTRUCTION. ALLOW SUN & MOON PERTURBATIONS TO DRIFT CONSTRUCTION BASE BACK INTO NOMINAL ORBIT PLANE AT COMPLETION OF CONSTRUCTION.

(FT/SEC)	THRUST (N)	MASS OF CONSTRUCTION BASE	THRUST DURATION	PROPELLANT MASS
72	1680	8.36×10^6 KG	30 HRS	2.3×10^3 KG

THIS COMPARES WITH 10.4×10^3 KG PROPELLANT FOR PERIODIC CORRECTIONS DURING CONSTRUCTION CYCLE.

1775-233W

Figure 68 SPS GEO Construction – Sun & Moon Gravitational Effects

Two options for nulling this motion have been considered. The first option, which minimizes propellant requirements to both the construction base and the satellite, is to pre-set the orbit inclination of the construction base orbit to approximately - 0.4° and allow the perturbing gravitational forces to drift the orbit to the operational inclination. At the time construction of the satellite is completed, the satellite is not required to expend propellant to null-out this motion. Moreover, the construction base can perform the pre-set maneuver prior to the start of the construction cycle when its mass is lowest. Total propellant requirements have been estimated at 2.3×10^3 Kg. for each construction cycle.

The second option is for the construction base to periodically null out the out-of-plane motion during the construction operations. Translational maneuvers would be performed by the construction base at designated times in the construction cycle corresponding with the time the construction base is near the center of mass of the combined construction base/satellite. They occur at about 80 and 150 days of the construction cycle. Because the mass of the construction base and partially completed satellite at these times are relatively high, the propellant requirements as shown are somewhat higher.

- Solar Pressure Effects - Solar pressure has an effect on the SPS construction orbit (Figure 69) because of the larger area that is evolved during construction. Over a period of about 6 months the circular orbit distorts to an ellipse with an eccentricity of about 0.037. In addition the orbit period increases from 24 hrs to about 24 hrs, 5 minutes. Both the orbit shape and period return to nominal after about 1 year.

As the projected area of the construction base/satellite is increased over the construction cycle, the solar pressure acts to increase the overall altitude and consequently the orbit period. If this perturbation is left unchecked, the construction base will drift from a given longitudinal location at maximum rate of about 1.4° per day, resulting in a significant displacement from the starting construction location. This can be corrected by applying small periodic thrusting maneuvers. Corrective requirements have been estimated at about 30 ft/sec for each construction cycle.

The effects of orbit eccentricity however is not significant, providing the 24 hr orbit period is maintained. Ellipticity causes an apparent longitudinal cyclical drift over a 24-hr period. This drift is estimated to reach a maximum

SOLAR PRESSURE EFFECTS

- CAUSES SMALL CHANGE IN ECCENTRICITY ($\approx$0.037 MAX) AND ORBITAL PERIOD ($\approx$ 5.4 MIN. MAX) WHICH IS SUBSEQUENTLY RESTORED, OVER A PERIOD OF 1 YEAR
- ECCENTRICITY CHANGE, IF UNCORRECTED, RESULTS IN A MAXIMUM LONGITUDINAL DRIFT OF $\approx \pm 4°$ EACH DAY AFTER 170 DAYS
- REQUIRES A $\Delta V \approx 180$ FT/SEC (22,000 KG) TO LIMIT DRIFT TO $\pm 1°$

RECOMMENDED PROCEDURES

- CORRECT ORBITAL PERIOD VARIATIONS TO PREVENT CONTINUOUS DRIFT. REQUIRES ≈ 30 FT/SEC (3,800 KG) OVER EACH CONSTRUCTION PERIOD
- ALLOW CONSTRUCTION BASE/SATELLITE TO DRIFT CYCLICALLY DUE ORBIT ECCENTRICITY VARIATIONS.

1775-234W

Figure 69 SPS GEO Construction – Solar Pressure Effects

of ±4 degrees per day after about 6 months. It is assumed that this variation is acceptable during construction operations and consequently not accounted for in estimating stationkeeping requirements. To limit this cyclical drift to ±1° per day maximum would require a ΔV of about 180 ft/sec per satellite construction period, or approximately 22,000 Kg of propellant.

- Ellipticity of Earth's Equatorial Plane - The effect of earth's ellipticity (Figure 70) causes a geosynchronous satellite to drift toward the minor axes of the earth's ellipsoid. These stable points are located at approximately 120° W and 60° E longitude. If uncontrolled, a satellite will drift as far past these stable nodes at its original longitudinal displacement, return, and then repeat the cycle. A construction base, for example, placed at 75° W longitude would drift past the western hemisphere stable point to a longitude of 165° W, or to a 90° longitude difference. It would return to the original position after approximately 18 weeks.

  This perturbation can be controlled by applying periodic corrections during the construction period. Propellant requirements have been estimated at about 750 Kg per construction cycle or 1500 Kg per year.

2.3.6 GEO Base Flight Control System

The GEO Base flight control system uses six electric ion propulsion modules. which are common with the EOTV attitude control system, to maintain the emerging satellite in an off-sun POP orientation. EOTV ion thruster panels provide ample control authority for peak torque conditions, as shown in Figure 71, whereas the SPS panels do not provide sufficient base control unless resized. The electric ion propulsion modules are located at the outer corners of the antenna platform (level C), solar-collector facility legs (level B) and the top decks (level J). Each module consists of a gimbal, yoke, thruster panel, propellant tanks, and thermal control. The gimballed modules are inhibited from firing either toward the base or any part of the constructed satellite. Chemical propulsion is also provided on each module to control the satellite/base attitude during occultation periods. during the on-sun roll maneuver, and subsequent operations for satellite test and checkout.

The propellant requirements for operating the GEO base in the SPS off sun POP flight mode are summarized in Figure 72. Almost 100MT of propellant is required each year for GEO base attitude control, station keeping, and base transfer functions.

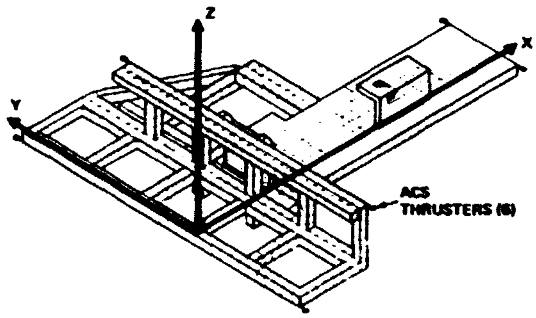
- CAUSES CONSTRUCTION BASE/SATELLITE TO DRIFT SLOWLY TOWARD MINOR AXES OF EARTH ELLIPSOID (MINOR AXES LOCATED AT LONG OF 120° W AND 60° E
- CONSTRUCTION LOCATIONS OVER CONUS MAY EXPERIENCE A LONGITUDE DRIFT OF UP TO 90° OVER A PERIOD OF 9 WEEKS

RECOMMENDED PROCEDURES

- APPLY PERIODIC CORRECTIONS DURING THE CONSTRUCTION CYCLE TO MAINTAIN DRIFT WITHIN ACCEPTABLE BOUNDS. REQUIRES A MAXIMUM YEARLY PROPELLANT OF ≈ 1500 kg

1775-235W

Figure 70 SPS GEO Construction – Effects of Ellipticity of Earth's Equatorial Plane



- LOW PROPELLANT ION THRUSTERS-COMMON TO SPS/EOTV EMPHASIZED
- GIMBALLED ION THRUSTER CTL FIRES AWAY FROM SPS & BASE
- CHEM PROPULSION USED FOR OCCULTATION & ON-SUN ROLL MANEUVER

MISSION PHASE	PEAK TORQUE*			ION THRUSTER PANEL TORQUE*					
				SPS-150N @ 20000 SEC			EOTV-430N @ 8000 SEC		
	X	Y	Z	X	Y	Z	Z	Y	Z
A	1	16	3	540	1080	1080	3020	6035	6036
B	77	155	12	540	↓	1080	↓	↓ PREFERRED	↓
C	119-802	589-41	31-2120	540	↓	1080	↓	↓	↓
D	739	219	224	540	↓	1080	↓	↓	↓
E	1070	889	1800	540	1080	1080	3020	6035	6036

*10³N-m

INSUFFICIENT CONTROL

1775-236W

Figure 71 GEO Base Flight Control Thrusters

6 MO. CONSTRUCT CYCLE REQMT	MASS (KG)
ATTITUDE CONTROL	37030
STATION KEEPING	6850
• SUN & MOON PLANE CHANGE	(2300)
• SOLAR PRESSURE	(3800)
• EARTH ELLIPTICITY	(1750)
BASE TRANSFER	1000
CONTINGENCY (10%)	4488
TOTAL	49370 KG

RECOMMENDATIONS FOR FUTURE STUDY

- ANALYZE & COMPARE CHEMICAL VS ELECTRIC PROPULSION SYSTEMS
- EVALUATE ATTITUDE STEERING TECHNIQUES & ALTERNATE FLIGHT ATTITUDES
- EXAMINE ATTITUDE CONTROL EFFECTS DUE TO BASE/SPS STRUCTURAL FLEXIBILITY & MOMENTUM TRANSFER INTERACTIONS

1775-237W

Figure 72 GEO Base Flight Control Propellant Requirements & Areas for Future Study

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Recommended areas for future study are also listed in Figure 72 and identified below.

- Conduct a comparison of chemical thruster systems versus electric propulsion systems for the attitude control and stationkeeping functions in terms of propellant consumption, electrical power requirements and reliability.
- Evaluation of "attitude steering" techniques and alternate flight attitudes to reduce propellant consumption during the construction phase.
- Consideration of factory/SPS structural flexibility during construction and momentum transfer during factory transfer relative to attitude control.
- Selection of attitude sensor concepts required during construction.

2.4 BASE ELECTRICAL POWER

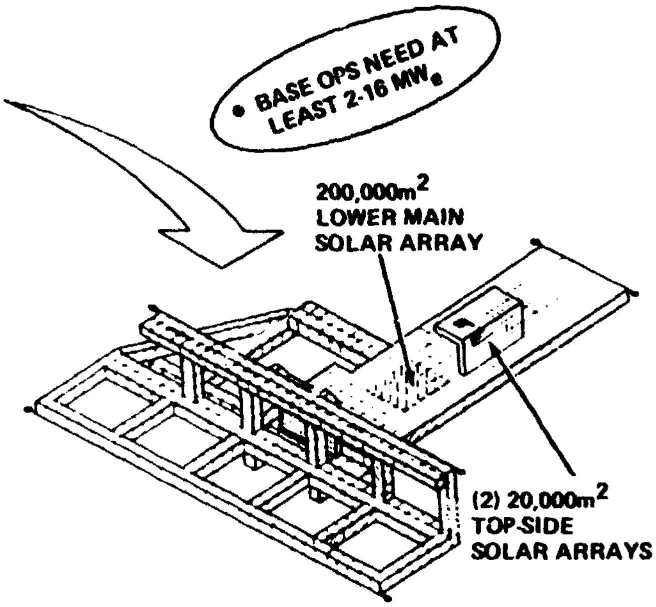
The GEO Base electrical power requirements shown in Figure 73, are mainly derived from the previous Boeing study, which defined SPS LEO construction methods (Report D180-24071-1). Power requirements for crew modules have been revised to reflect more operative modules (15 vs 10) and also adjusted commensurate with the updated ECLS weight estimate. The 14,400 KW requirement for ion propulsion assumes that no more than four thruster panels would be fired simultaneously. Base electrical power requirements are further defined in Table 3.

The base electrical power system provides 1500KW for operative crew modules, construction equipment and external lighting. This sytem also provides 14,400KW to operate the low thrust ion propulsion flight control system. Fixed body mounted solar array blankets, which are similar to those on the satellite, are used for electrical power generation. To accommodate SPS off-sun/on-sun construction attitudes, base solar arrays are located underneath the antenna construction platform and also on the top and outer side of the antenna assembly facility, as depicted in Figure 73. It also has a nickel hydrogen battery energy storage system, which is used for brief periods during equinoctial occultation. Electrical power system sizing parameters are provided in Figure 73 and Table 4.

2.5 GEO BASE MASS AND COST ESTIMATE

The GEO Base work support facilities and crew support facilities are also described under WBS Element 1.2.1 in the Phase 2 Reference System Description Report, Volume 2 (D180-25461-2). The major elements of the GEO base are identified therein and described in terms of the related WBS dictionary, system description, design basis,

POWER REQM'TS	KW	BASIS
15 CREW MODULES	1030	UPDATE 15 VS 10
ION PROP FLIGHT CTL	14400	4 THRUSTERS
CHEM PROP FLIGHT CTL	5	D180-24071-1
CONSTRUCTION EQUIP	150	
EXTERNAL LIGHTING	320	
TOTAL 15905 TO 1505 KW (W & W/O ION)		



SUBSYS ELEMENT	MASS	BASIS
SOLAR ARRAYS	102.2	0.426 Kg/m^2
NiHz BATTERIES	34.6	52 WH/Kg
POWER CONDITIONING	4	SCALED TO SPS
POWER DISTRIBUTION	53.6	
TOTAL 134.4 MT		

1775-251W

Figure 73 Base Electrical Power Definition

mass and mass basis, cost and cost basis, and required facilities for manufacture. A breakdown of the GEO base mass and cost data is provided in Figure 74 for the construction base facilities. Phase 1 information (D180-25037-3) was used for costing the GEO facility structure, construction equipment, cargo handling and distribution system, subassembly factories and work support modules. Equipment quantities were updated as needed and all production cost data were escalated to 1979 dollars. Phase 2 information includes the areas of base subsystems (flight control and electrical power), crew quarters and full scale development costs for the elements listed. Limited study resources have precluded a final design iteration and updating across the board.

TABLE 3 BASE OPERATING POWER REQUIREMENTS

OPERATING POWER		KW
CREW MODULES		(1030)
ENVIRONMENT CONT/LIFE SUPPORT	430	
INTERNAL LIGHTING/CREW ACCOMMODATION	530	
INFORMATION SYSTEM	70	
FLIGHT CONTROL		(14405)
GUID & CONT & CHEM PROP	5	
ION PROPULSION	14400	
CONSTRUCTION EQUIPMENT		(150)
SATELLITE EQUIPMENT	50	
ANTENNA EQUIPMENT	50	
SUBASSEMBLY	50	
EXTERNAL LIGHTING		(320)
SATELLITE CONST.	120	
ANTENNA CONST.	120	
SUBASSY/WAREHOUSE	80	
TOTAL	15305 KW	

1775-244W

TABLE 4 SOLAR ARRAY SIZING

PARAMETER	CONTROL MODE: ION FLT CTL	CONTROL MODE: CHEM. FLT CTL
• TOTAL POWER REQUIREMENTS (KW)	(24820)	(2440)
• OPERATING LOAD	15905	1505
• SECONDARY POWER SUPPLY RECHARGING	80	80
• POWER CONDITIONING (20%)	3180	300
• POWER DISTRIBUTION (30%)	4470	450
• RADIATION DEGRADATION (5%)	1185	115
• SOLAR ARRAY SIZING		
• CONTINUOUSLY SUN ORIENTED ARRAY: (SATELLITE TYPE CELLS, 142w/m^2)	117000m^2	17400m^2
• FIXED BODY MOUNTED ARRAY WITH POP ORIENTED CONST. BASE		
• MAX SUN INCIDENCE ANGLE OF 23.5 DEG		
• ARRAY SIZE/LOCATION	193000 X 200000m^2 UNDER ANTENNA PLATFORM	18700m^2 OR 20000m^2 OUTER SIDE & TOP ANTENNA FACILITY

1775-245W

The GEO Base annual resupply requirements are defined in Figure 75 for the baseline construction facilities. The resupply requirements for SPS add-on maintenance facilities are also defined in the figure for supporting 20 to 60 satellites.

Future studies on the GEO Base should focus on those issues which will lead toward updating and expanding the base system mass and cost data. Specifically the base structural design needs to be updated and sized for dynamic effects due to construction, intra base logistics, and resupply. Methods for building the construction base in orbit also need to be addressed and defined for implementing GEO base full scale development. Further work is also required on defining the features of the beam builder substations, cherry pickers, power bus dispensers etc. The base cargo handling system and subassembly factories also require further analysis and updating. Other elements of the GEO base should also be addressed. These areas include facilities for test and check out, OTV servicing, base maintenance and base command and control systems. In addition the base flight control and electrical power subsystems should be reexamined.

WBS ELEMENT	MASS, MT	COST – 1979 $M DELTA DEV.	COST – 1979 $M PROD	DATA BASE
1.2.1.1 WORK SUPPORT FACILITIES	4762	> 767	3212	
.1 STRUCTURE	2927	107 **	337	ο1
.2 CONSTRUCTION EQUIP	460	660	1800	ο1 ADJ
.3 CARGO HDLG/DISTRIBUTION	399	ND	430	ο1 ADJ
.4 SUBASSEMBLY FACTORIES	38		323	ο1
.5 TEST/CHECKOUT FACILITIES	ND *		ND	
.6 TRANSPORT VEH. MAINTENANCE	ND		ND	
.7 SPS MAINT. SUPT FACILITIES	ND		ND	
.8 BASE SUBSYSTEMS	938		322	ο2
.9 BASE FACILITEIS & EQUIP. MAINT.	ND		ND	
.10 COMMAND & CONTROL SYS	ND	ND	ND	
1.2.1.2 CREW SUPPORT FACILITIES (CONSTR)	1628	> 2271	2554	
.1 CREW QUARTERS	1215	2271 ***	1923	ο2
.2 WORK MODULES	413	ND	631	ο1 ADJ
WRAPAROUND COSTS (47%) PROJ MAT. SE & I, SYS TEST INST ASSY & C/O, GSE & SPARES		1428	2710	
1.2.1 GEO CONSTRUCTION BASE FACILITIES	6390	> 4466	8476	

* ND – NOT DETERMINED
** EXCLUDES MINI FACILITY TO BUILD BASE
*** INCLUDES NEW 8 STORY MANUFACTURING PLANT

1775-252W

Figure 74 GEO Base Mass & Cost Breakdown

RESUPPLY ITEM \ MASS-MT	CONSTR OPS 444 CREW	SPS MAINT OPS 383 TO 1149 CREW		BASIS
CREW SUPPLIES (FOOD, HOUSEKPG, ETC)	418	361 TO	1081	DET EST & PRIOR STUDIES
CREW MODULE SUPPLIES (O_2, N_2, H_2O, ECLS PARTS ETC)	190	151 TO	454	EST ECLS & GUESS ETC
WORK MODULE SUPPLIES	126	108 TO	323	SCALED TO HAB. UNITS
WORK FACILITY SUPPLIES	398	(ND)	(ND)	
CONSTR EQUIP PARTS	37	–	–	GUESS 2%/QTR
CARGO HDLG/DIST PARTS	32	–	–	GUESS 2%/QTR
CREW BUS (O_2, N_2)	7	–	–	SHUTTLE LEAKAGE
SUB ASSY FACTORY PARTS	3	–	–	GUESS 2%/QTR
REMOTE WORK STA (O_2 N_2 & PARTS)	145	ND	ND	MRWS EST
BASE SUBSYS PARTS	75	–	–	GUESS 2%/QTR
FLT CTL PROPELLANTS	99	–	–	ESTIMATE
BASE MAINT & TEST PARTS	ND*	–	–	–
TRANSPORT VEH MAINT PARTS	ND	–	–	–
SPS MAINT SUPT PARTS	–	ND	ND	–
TOTAL	1125MT	620 TO 2478 MT		

* ND – NOT DETERMINED

1775-253W

Figure 75 GEO Base Resupply Requirements (W/10% Contingency)

3 - CREW MODULE UPDATE

The crew support facilities for the SPS GEO base are required to house several hundred people, support multiple work schedules, and support essential base functions such as the typical control center depicted in Figure 76. Pressurized crew modules are required for daily crew habitation, transient crew accommodations, command and control facilities, base maintenance and other work support functions. All GEO base crew quarter modules and work modules are to be compatible with the HLLV payload bay (23m x 17m dia). The 100 man habitat, described in Boeing's earlier SPS document (D180-24071-1), had been scaled from a prior Rockwell study on 12 man unitary space stations in LEO.

Grumman was requested to review and update the 100 man crew module concept during Phase 2, since it is a major element of GEO base cost. As a consequence, the habitat design requirements were reexamined for internal crew arrangement, radiation protection and environmental control/life support functions.

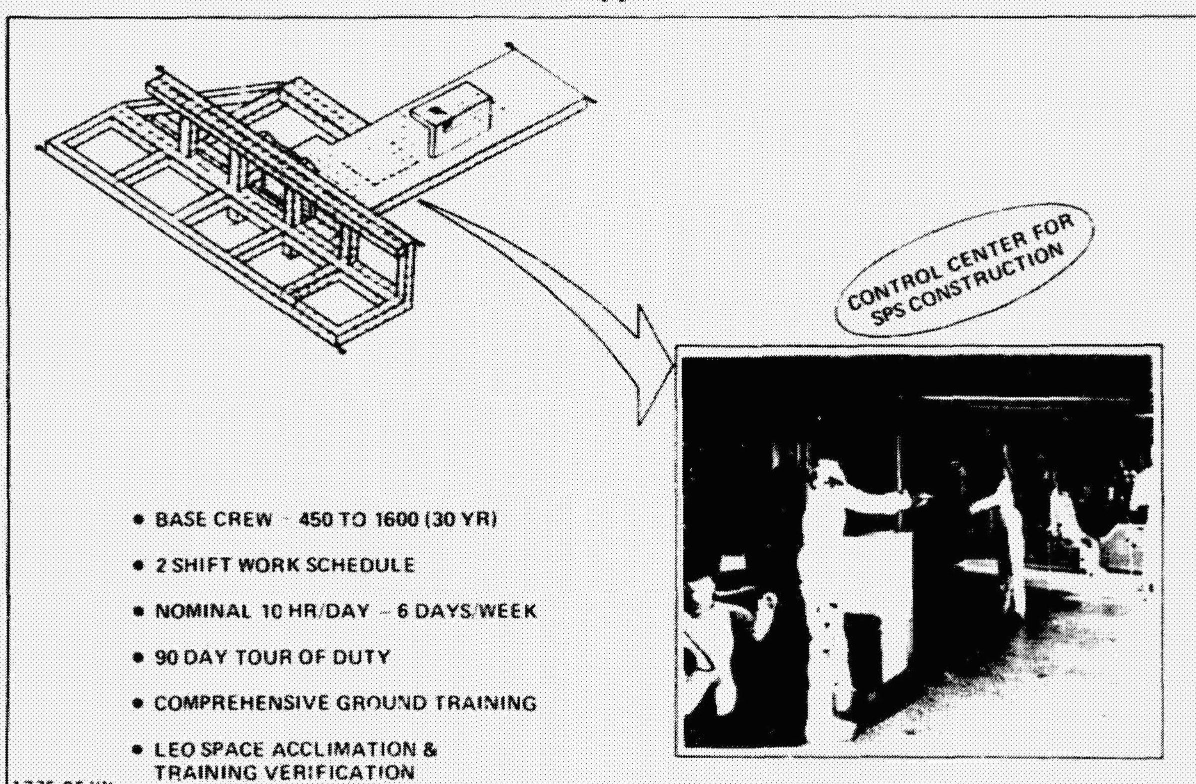
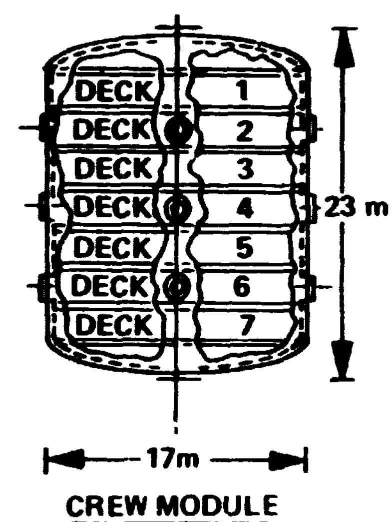


Figure 76 GEO Base Crew Operations

Some of the more important requirements used to design the crew module are listed in Figure 77. The first four requirements establish the size and interfaces of the crew modules. Interior accommodations obviously must be designed for zero g operation. However, to prevent crew disorientation, they should all be designed to a common reference. One-g was selected, as this facilitates ground operations and is satisfactory for space activities. Based on the Navy projection for support ships, GEO base crew accommodations should plan for 75% male and 25% female. In addition, meteroid and solar storm radiation protection must also be provided.

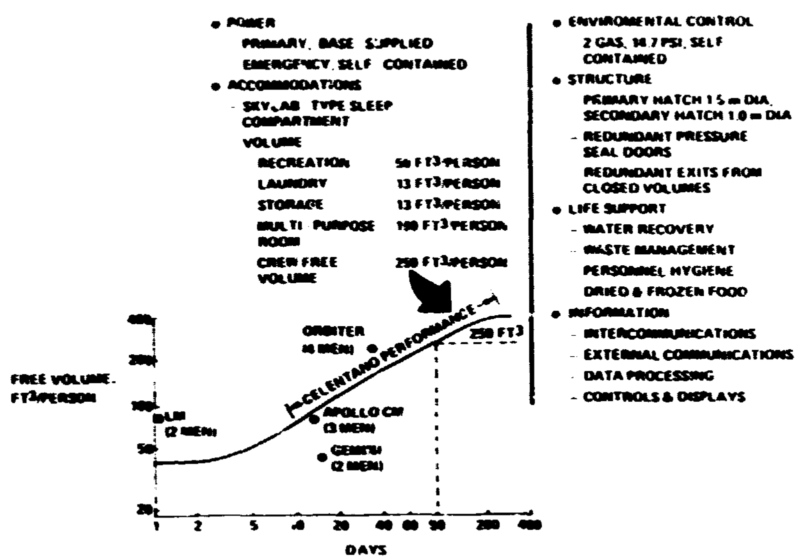
Each crew module is also required to operate almost independently, except for primary electrical power and orbital attitude, which is provided by the base. Crew module subsystem requirements are summarized in Figure 78. Emergency power, environmental control, life support and information subsystems are to be self-contained within each module. Accommodation requirements are based on government and industry studies. Hatches are sized to permit transfer of equipment and are generous for IVA. The environmental control subsystem operating pressure is stated as nominal earth value. However, it could be operated at a lower value (i.e. 10 PSIA, maintaining O_2

- SIZE (17m DIA X 23m LONG) COMPATIBLE WITH HLLV
- ACCOMMODATIONS FOR 100 PEOPLE
- DESIGN LIFE: 30 + YEARS
- BERTHING/DOCKING/AIR LOCK COMPATIBLE WITH CREW BUS & LOGISTICS & MODULE
- STRUCTURAL ATTACHMENT TO BASE
- DESIGN FOR ZERO G OPERATIONS
- INTERIOR LAYOUT ONE G
- CREW 75% MALE, 25% FEMALE
- METEOROID & SOLAR STORM RADIATION PROTECTION



1775-255W

Figure 77 Crew Module General Requirements



1775-256W

Figure 78 Crew Module Subsystem Requirements

partial pressure) thereby possibly reducing structural design requirements, and eliminating prebreathing requirements, should emergency EVA be required.

3.1 100 MAN HABITAT ARRANGEMENT

Area allocations were examined for the baselined crew module size. Figure 79 depicts a domed end cylinder housing 100 crew members with dedicated work stations. The pressure shell diameter is 16.5 m and the external diameter is 17.0 m. A nominal 0.25 m has been tentatively allotted for thermal insulation, radiation protection and radiator wraparound functions. The pressure vessel is 23.0 m long. Seven decks have been provided, each having a 2.2 m floor to ceiling height. The structure between each deck is 0.3 m thick, providing volume for installation of wiring, ducting, lighting, insulation, etc. Decks 2 and 6 have two (2) berthing ports located 90° to each other, while Deck 4 has only one (1) port. These berthing rings are configured to mate with berthing ports on Spacelab-type modules. The attached Spacelab modules provide the services and re-supplies to keep the modules operational. Larger diameter berthing or docking rings are located at each dome end for mating with the base structure, another module or the transportation delivery vehicles (HLLV or EOTV). Each deck contains 16 to 18 viewing windows around its periphery.

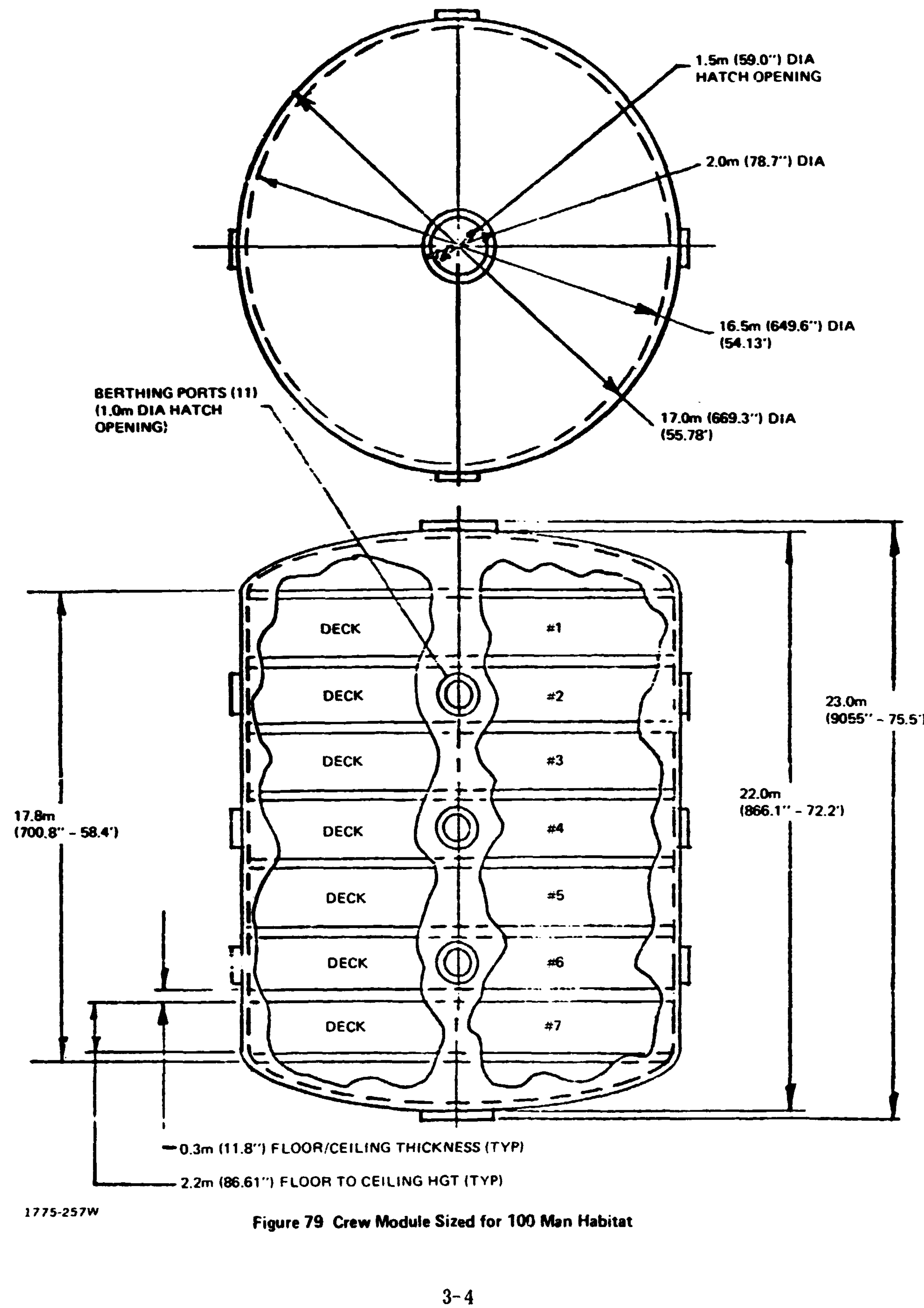


Figure 79 Crew Module Sized for 100 Man Habitat

Preliminary section cuts of the 7 deck module are shown in Figures 80 and 81. Decks 1,3 and 7 have been allotted for the living quarters for 100 crew members, both male and female. Deck 1 is configured to house the management-type personnel in 16 various sized one and two men staterooms for a total of 24 people. A large waste management compartment and personal hygiene compartment are provided to handle the occupants on this deck. Deck 3 has four staterooms and 18 crew quarters to house 36 persons. It also contains a W/M and personal hygiene compartment. Deck 7 has 24 crew quarters, a W/M and personal hygiene compartment to accommodate 40 people. The density factor of each deck is varied according to job title on board the space base. Providing for more than 100 people in this size module is not recommended.

Deck 2 contains a control center. A total of 25.44 square meters of displays and controls has been provided to monitor space base and module parameters. The controls need not be duplicated in each of the four modules, but should be overlapped. In the event of a module shutdown, control of the base should still be possible by virtue of the instrumentation remaining in the other three modules. A large room is provided for all facets of EVA hardware.

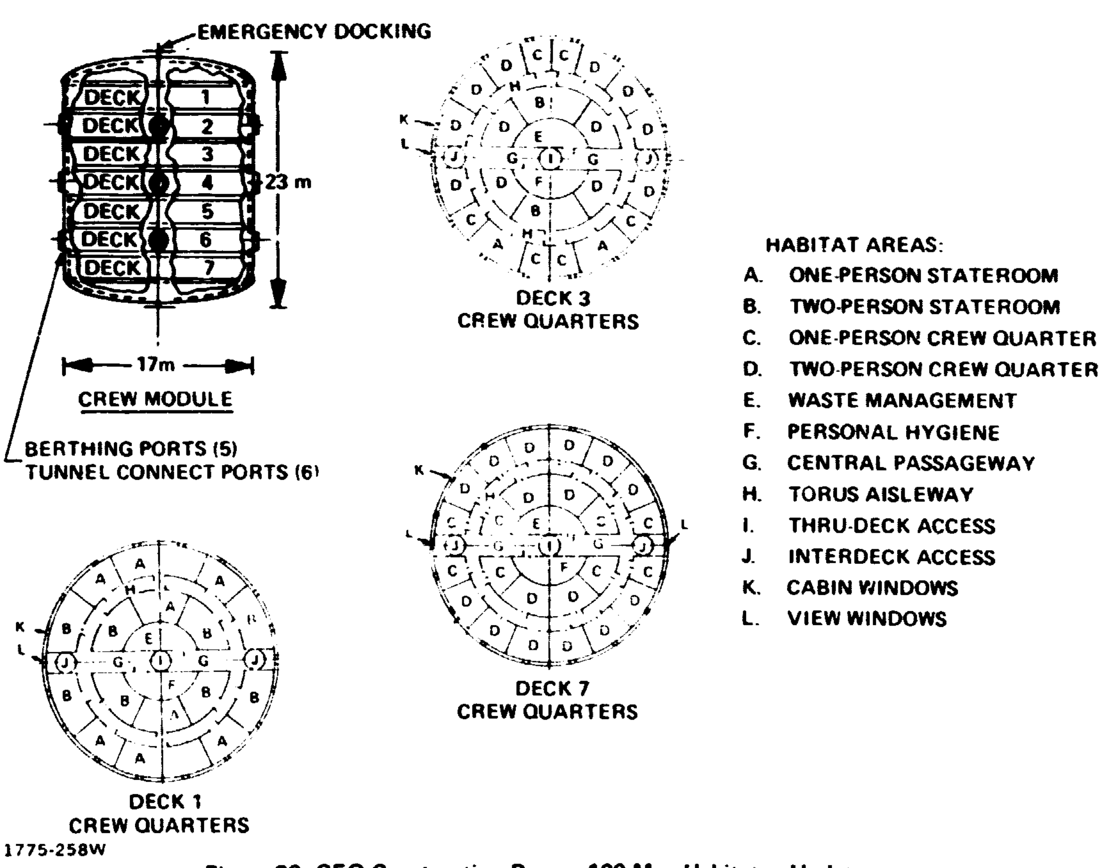
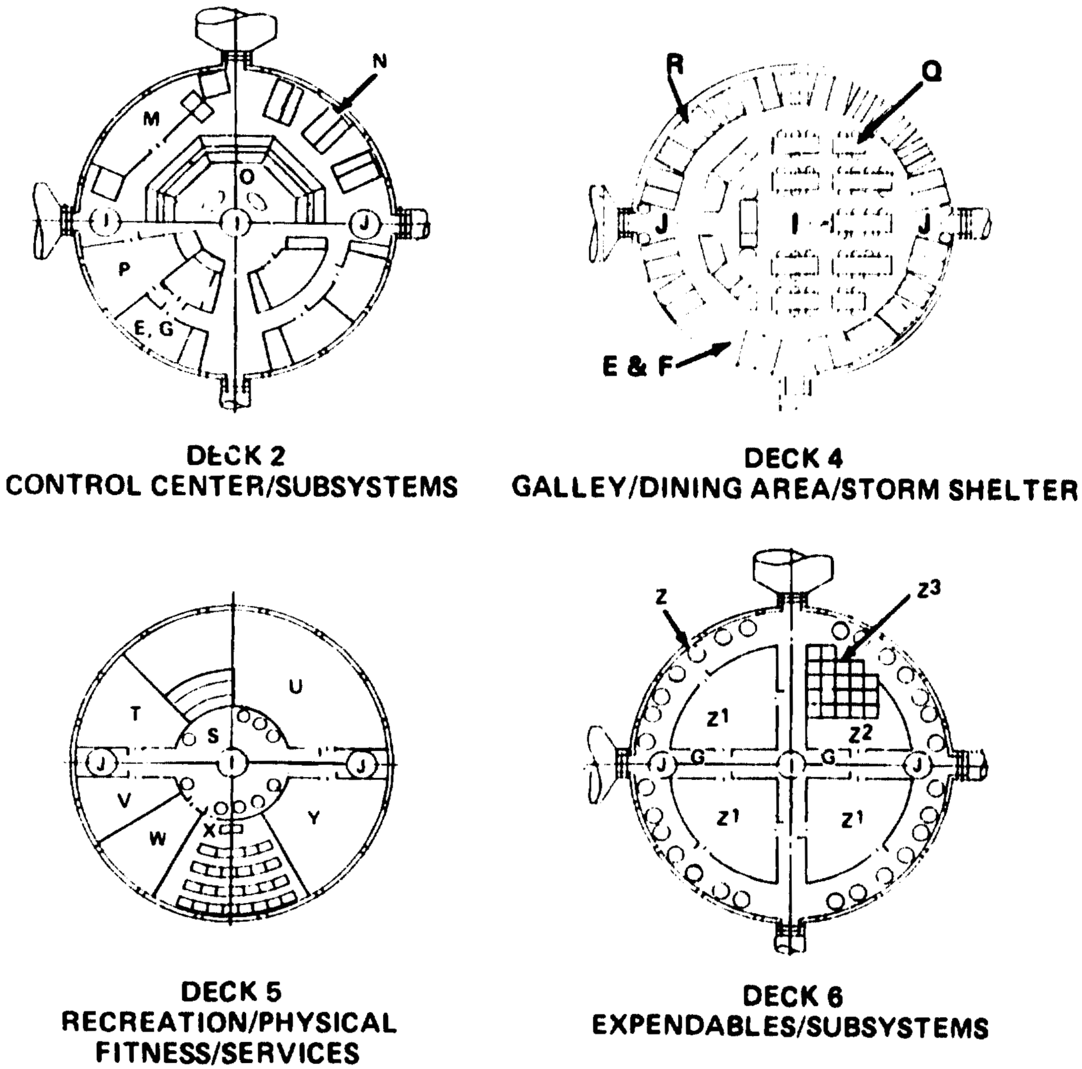


Figure 80 GEO Construction Base — 100 Man Habitat — Update



HABITAT AREAS:

- M. EMU/EVA PREP ROOM
- N. COMPUTER RACKS
- O. CONTROL CENTER
- P. CONFERENCE ROOM
- Q. DINING AREA (56 PERSONS)
- R. FOOD STORAGE
- S. LOUNGE
- T. LAUNDRY/SUPPLIES
- U. RECREATION/GYMN
- V. BARBER SHOP/POST OFFICE
- W. LIBRARY/STUDY
- X. THEATER/CHAPEL
- Y. SICK BAY/DENTIST
- Z. EXPENDABLES
- Z1. SUBSYSTEMS
- Z2. AGRICULTURAL STUDY
- Z3. COMPACTED WASTE

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Figure 81 GEO Construction Base — 100 Man Habitat — Update (Cont'd)

Deck 4 has been arranged to accommodate dining facilities for 56 people at one setting. The food serving center contains combination hot air/convection/resistance ovens for heating food, and is the area where the food is dispensed to the diners, cafeteria style. The return rack is the area where used dishes and food are placed. Compactors and dishwashers are located here. Up to 100 people can also be accommodated in Deck 4, when used as a radiation shelter.

Deck 5 is recreational/physical fitness/services area. The central area is 6 m in diameter and serves as a lounge area. From this lounge, access can be obtained to the snack bar, barber shop, post office, chapel, theatre, library, gym and recreation area, and sick bay/dentist areas.

Deck 6 contains tanks for storage of expendables and three large rooms for subsystem equipment and hardware. The fourth quadrant contains storage for waste bales and an area for agricultural study.

Each deck is accessible to the adjacent deck via three (3) 1.5 m diameter openings. In general, the decks have a 1.5 m wide central aisle passageway and a torus aisleway 1.0 m wide.

3.1.1 Allocation for Crew Habitat Floor Area

The Habitat Module, as shown in Figures 80 and 81, provides for 100 crew members on seven (7) decks. The total floor area for all decks is 16,000 $ft.^2$ ($1497m^2$), or 160 square feet per person. Assuming half the floor area is occupied with walls, furniture, equipment, sub-systems, etc., 80 square feet of habitable area is available for each person.

Celentano's recommended free volume per man for acceptable crew performance is included in the GEO Base crew module subsystem requirements. As previously shown in Figure 78 Celentano's free volume curve indicates that 250 $ft.^3$ is required for each person on a 90 day mission. Assuming a 7.2 ft. ceiling height, 34.7 $ft.^2$ ($3.22m^2$) of floor area is required for each crew member. This allocation of crew floor area compares favorably with current Navy ship design practice. For example, NAV Spec OPNAV9930.5A, "Environmental Control Standards for Ships of the U.S. Navy," lists the crew quarters requirements for each type of crew member. It does not however, list the total floor area requirements on various ships for each person. Table 5 compares the Navy requirements listed on the left with equivalent areas provided in the 100 man SPS Habitat (Figures 80 and 81). The first number shown in the Habitat

TABLE 5 CREW FLOOR AREA COMPARISON

NAVY CLASSIFICATION	NET FLOOR AREA PER CREW MEMBER (FT²)			HABITAT CREW
	SUBS	SURFACE VESSELS	SPS HABITAT*	
CREW:				
• SINGLE (CPO)	3	9-13	(42-60) 21-30	CREW QUARTERS
• DOUBLE (CPO)	3	9-13	(30-36) 15-18	CREW QUARTERS
• ENLISTED PERS	2.5	6-7	–	(NO EQUIVALENT)
OFFICERS STATEROOMS:				
• SINGLE	12	50	(70-76) 35-38	OFFICERS STATEROOM
• SINGLE (EXEC.)	40-70	40-70	(82) 41	EXEC. STATEROOM
• DOUBLE	6	20-35	(41-53) 21-27	OFFICERS STATEROOM
• CMDING OFFICER	50-80	50-80	(140) 70	MASTER STATEROOM
• BUNK ROOM (2 OR MORE)	5	20	–	(NO EQUIVALENT)

*TOTAL FLOOR AREA ( ) – 50% ASSUMED USABLE

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column is the total floor area in each room; the second number is 50% of total. It is assumed 50% of the floor area is taken by furniture, sleeping bags, lockers, etc.

It can be seen that the crew quarters floor areas in the SPS Habitat exceed the Naval specs and compare favorably with officers quarters. The Habitat has a maximum of 2 persons in a room, while the Navy uses up to 6. It appears, the quarters provided in the Habitat are more spacious and afford more privacy than those provided aboard ships.

A detailed analysis of the 100 person Habitat is provided in Table 6. Each area is listed on each deck with the total floor area noted. An estimated percentage factor is listed after each number, representing the net area in a space, which can be walked upon or occupied by a crew member. The last column on each line therefore represents the useable floor area for the crew.

The total floor area of 8210 sq. ft. ($763m^2$) represents the net floor area in the Habitat that is available to the crew for free movement. This net area divided by 100 represents 82.1 sq. ft. ($7.63m^2$) of free floor area for each crew man. This is more than twice the area derived from Celentano's free volume design performance criteria.

The 16.5m diameter x 17.8 m. long 100 man-habitat is estimated to weight 243,100 kg. Therefore the impact of allocating added crew floor area is 3.19 kg/m^2 per person for habitats of this size.

3.1.2 Crew Accommodations

In addition, the major areas of the crew accommodations subsystem were identified and the requirements for feeding 100 people for 90 day periods were analyzed to establish weight and volume data for determining logistic support and onboard storage requirements.

SPS Crew Accommodations subsystem includes ten general areas as listed below:

1.0) Food, Food Storage, Preparation and Disposal

2.0) Dining Area & Implements

3.0) Crew Quarters

4.0) Crew Provisions/Personal Gear

5.0) Housekeeping Equipment/Supplies

6.0) Housekeeping Waste

TABLE 6 HABITAT USABLE CREW AREA

	ELEMENT FLOOR AREA (FT^2)	% FACTOR FOR NET AREA	NET AREA (FT^2)
DECK NO. 1			
1. STATEROOMS	1392	50	696
2. TORUS AISLEWAY	347	80	278
3. CENTRAL PASSAGEWAY	268	80	214
4. INTERDECK ACCESS	59	100	59
5. W/M & PERS. HYG.	180	25	45
		SUBTOTAL	1292
DECK NO. 2			
1. EMU/EVA PREP & REPAIR	133	30	40
2. CONFERENCE ROOM	141	50	70
3. W/M & PERS. HYG.	75	25	19
4. OFFICE	63	40	25
5. SHOP	72	40	29
6. PHOTOGRAPHY ROOM	72	40	29
7. EQUIPMENT ROOM	40	20	8
8. INTERDECK ACCESS	59	100	59
9. OPEN AREAS/AISLES	1101	75	826
		SUBTOTAL	1105
DECK NO. 3			
1. CREW QUARTERS	1008	50	504
2. STATEROOMS	374	50	187
3. W/M & PERS. HYG.	180	25	45
4. CENTRAL PASSAGEWAY	268	80	214
5. TORUS AISLE	347	80	278
6. INTERDECK ACCESS	59	100	59
		SUBTOTAL	1287
DECK NO. [illegible] (REVISED LAYOUT)			
1. DINING AREA	750	70	525
2. W/M & PERS. HYG.	60	25	15
3. INTERDECK ACCESS	59	100	59
4. AISLEWAYS	175	80	140
		SUBTOTAL	739
DECK NO. 5			
1. LOUNGE	295	90	266
2. SNACK BAR	65	25	16
3. LAUNDRY/SUPPLIES	205	30	62
4. RECREATION/GYM	637	70	446
5. BARBER/POST OFFICE	132	40	53
6. LIBRARY/STUDY	160	50	80
7. THEATRE/CHAPEL	332	70	232
8. SICK BAY/DENTIST	292	40	117
9. INTERDECK ACCESS	59	100	59
10. CENTRAL PASSAGEWAY	127	80	102
		SUBTOTAL	1433
DECK NO. 6			
1. TORUS AISLE	626	80	501
2. CENTRAL AISLE	444	80	355
3. INTERDECK ACCESS	59	100	59
4. SUB-SYSTEMS ROOM	484	20	97
5. STAB & CONTROL ROOM	242	20	48
6. AGRICULTURE STUDY	108	20	22
		SUBTOTAL	1082
DECK NO. 7			
1. CREW QUARTERS	1352	50	676
2. W/M & PERS. HYG.	180	25	45
3. CENTRAL PASSAGEWAY	268	80	214
4. TORUS AISLEWAY	347	80	278
5. INTERDECK ACCESS	59	100	59
		SUBTOTAL	1272
		TOTAL	8210

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7.0) Furnishings

8.0) Crew Support Facilities - Off Duty

9.0) Crew Support Facilities - On Duty

10.0) Passageways/Aisles/Mobility Aids

Using data supplied by NASA (MSC-03909 "Habitability Data Handbook-Volume 4 - Food Management"), a deeper cut was made into the first element listed above. The food requirement for one Habitat was determined in terms of food types, weight, packaging and volumes. Modular packages were established for the shelf stable, refrigerated and frozen foods. In turn, modular lockers were configured to house these food packages, so that they could be stored in minimum volume containers in the Habitat.

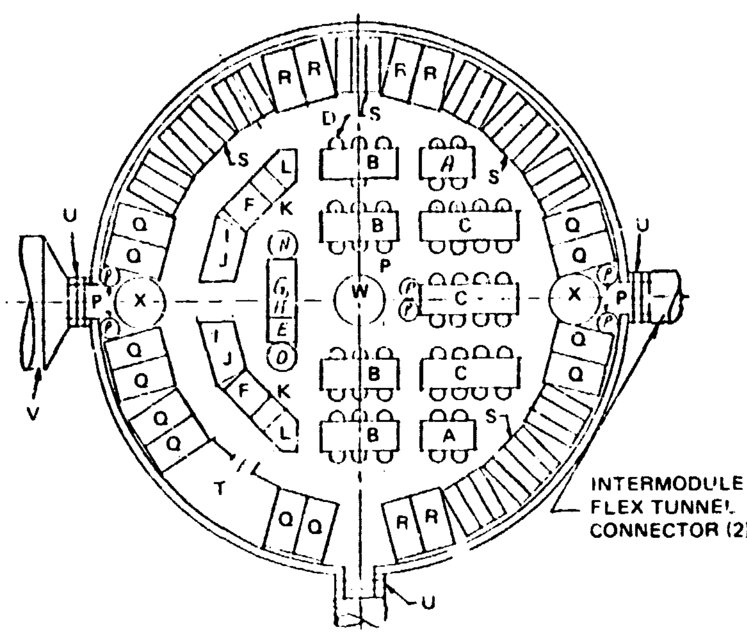
This study indicates that feeding 100 people for 90-day time periods requires 17,618 kg of food (71 m^3) to be delivered to each Habitat. Multiply this by eight (800 people) and it can be seen the logistics for this element alone is huge. It is apparent that further study in this area is warranted to see how this can be improved. Growing food on board the Habitat could be a possible solution.

Having established the food requirements, another layout was prepared of Deck No. 4 "Galley/Dining Area & Storm Shelter" to include improved radiation protection features. As shown in Figure 82 all food lockers are ringed around the outside pressure shell. This mass of hardware adds to the effective shielding during high radiation periods. The increased volume for food storage, the peripheral arrangement of the lockers and further definition of ovens, compactors, etc., resulted in a smaller area available for diners. This new arrangement can seat only 56 people, as compared to 60 in the previous study. It is assumed that further studies on food and dining requirements will reduce this number some more.

By moving the tables to one area, the open area can serve as a storm shelter for 100 people for short time durations.

3.1.3 100 Man Habitat - Typical Interiors

The Phase 2 crew module design effort consisted of a superficial investigation of compartmental partitioning of the habitat using estimated volumetric data for the equipments and its arrangement. The habitat galley arrangement and sizing was the only detail design effort afforded in the habitat preliminary design. Here the weight



	DESCRIPTION	QTY	SIZE (IN.) (W x L x H)	FLOOR AREA FT^2	FLOOR AREA M^2	UNIT VOL. FT^3	UNIT VOL. M^3	TOTAL VOL. FT^3	TOTAL VOL. M^3	COMMENTS
A	DINING TABLE – 4	2	34 X 64 X 36							SEATING
B	DINING TABLE – 6	4	34 X 96 X 36	750	69.68					FOR
C	DINING TABLE – 8	3	34 X 120 X 36							56
D	ZERO "G" SEATS	56	– – – – – – –							
E	OVENS	3	21 X 24 X 24	4.0	0.37	7.0	0.20	21.0	0.59	VERT. STACKED
F	TRASH COMPACTOR	2	48 X 48 X 48	32.0	2.97	64.0	1.81	128.0	3.62	BELOW COUNTERTOP
G	FOOD PREPARATION	1	36 X 66 X 48	16.5	1.53	66.0	1.87	66.0	1.87	COUNTERTOP
H	DISHES STOW.	1	36 X 66 X 24	–		33.0	0.93	33.0	0.93	ABOVE G
I	FOOD SERVING	2	36 X 66 X 48	31.0	2.88	66.0	1.87	132.0	3.74	COUNTERTOP
J	CONDIMENTS STOW.	2	36 X 66 X 24	–		33.0	0.93	66.0	1.87	ABOVE I
K	DISHWASHER	2	24 X 36 X 24	12.0	1.11	8.0	0.23	16.0	0.45	
L	DISH/FOOD RETURN	2	36 X 30 X 48	15.0	1.39	30.0	0.85	60.0	1.70	
M	STOWAGE CABINET	2	36 X 96 X 24	–		60.0	1.70	120.0	3.40	ABOVE F, K, I
N	WATER TANK – COLD	1	36 DX 72	7.1	0.66	42.0	1.19	42.0	1.19	314 GALLONS
O	WATER TANK – HOT	1	36 DX 72	7.1	0.66	42.0	1.19	42.0	1.19	314 GALLONS
P	WATER TANK – H/C	6	24 DX 72	18.8	1.75	18.5	0.52	111.0	3.14	828 GALLONS
Q	FREEZER	6	75 X 71 X 87	221	20.52	254	7.182	1522	43 092	SEE
R	REFRIGERATOR	3	75 X 71 X 87	110	10.26	254	7.182	761	21.546	TABLE
S	AMBIENT FOOD	33	17 X 64 X 87	256	23.81	254	1 587	1850	52.388	1-15
T	W/M & HYGIENE	1	72 X 120 X 87	60	5.57	432	12.23	432	12.23	
U	BERTHING PORT	3	60 DIA.	–						1 M HATCH
V	RESUPPLY MOD.	1	LONG MOD.	–		2,300	65.0	2,300	65.0	SPACELAB
W	THRU DECK ACCESS	1	–	19.69	1.82	–	–	–	–	
X	INTERDECK ACCESS	2	–	39.38	3.64	–	–	–	–	

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Figure 82 Deck No. 4 – Galley/Dining Area & Storm Shelter

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and volume of the food and its storage arrangement was looked at in some detail, since the galley provides crew dining and 100 man storm shelter accommodations.

Figure 83 illustrates some typical interiors which were established in an earlier Grumman study and may be used as examples of what a future SPS habitat interior might resemble.

3.1.4 Base Habitat Complex

One possible arrangement for accommodating the SPS GEO Base 400-man construction crew is shown by the crew habitat complex illustrated in Figure 84. Four (4) habitat modules, 17.0 meters in diameter, are grouped together in a geometric pattern. Initially each module is transported to this site by the large crane on the railroad system. The bottom of each module has a large berthing ring, which mates with one on the previously installed mounting platform. Guy wires (not shown) running to the Factory structure will provide stability to the installed module. The fifth module nestled between two of the habitat modules serves as an interim quarters module for 100 crew members. When all five modules are firmly installed, 12 interconnectors are installed. These connectors provide traffic flow between all the modules. Each habitat has five (5) radially located berthing ports to which the following Spacelab-type modules can be affixed:

- Short Spacelab (1) to serve as a 4-6 man EVA airlock
- Short Spacelab (1) to serve as an interface module for shirt sleeve transfer to another pressurized module, such as MRWS closed cabin cherry picker & MRWS free flyer
- Long Spacelab (1) to provide for a 90 day re-supply of food for 100 people
- Short Spacelab (1) to provide re-supply of expendables
- Short Spacelab (1) to provide storage for all waste which will be returned to earth.

The interim module has three (3) radially located berthing ports to which Spacelab type modules can be affixed.

3.2 RADIATION EXPOSURE & PROTECTION

Figure 85 shows the earth magnetosphere and the radiation sources to which SPS systems and the GEO assembly and maintenance crew will be subjected. The

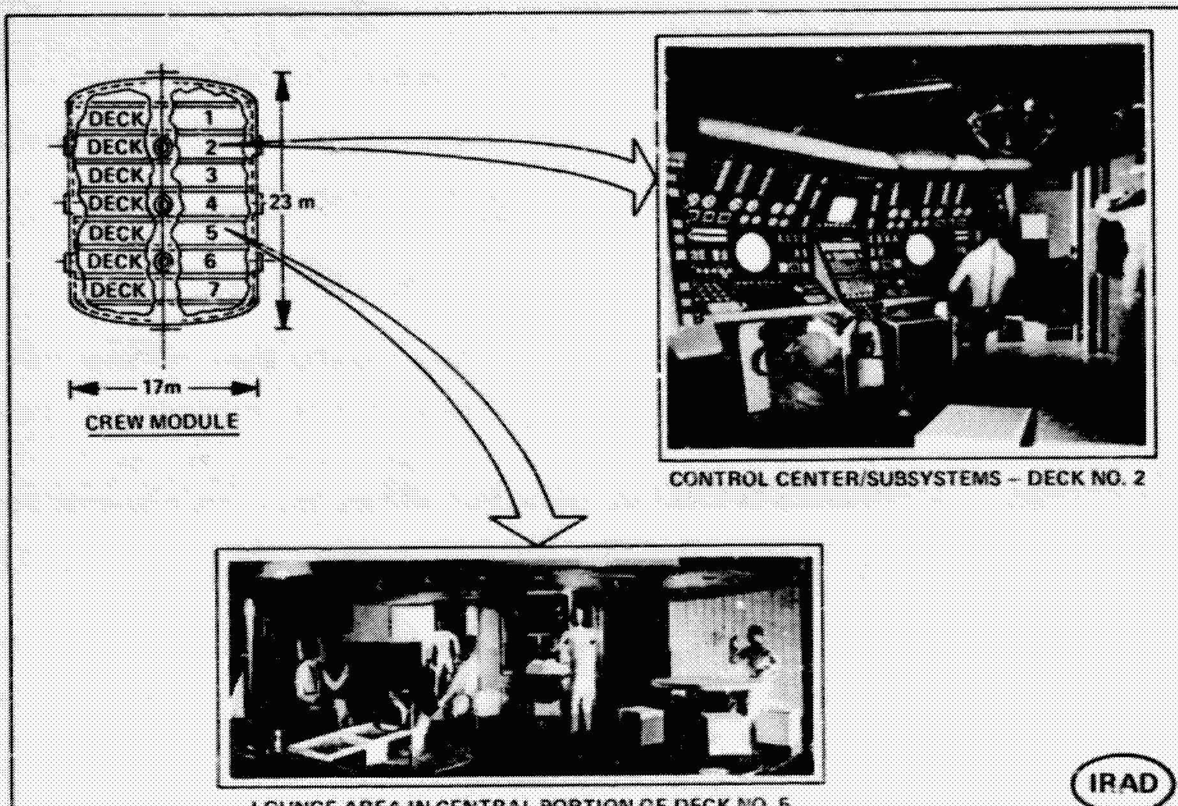

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Figure 83 100 Man Habitat – Typical Interiors

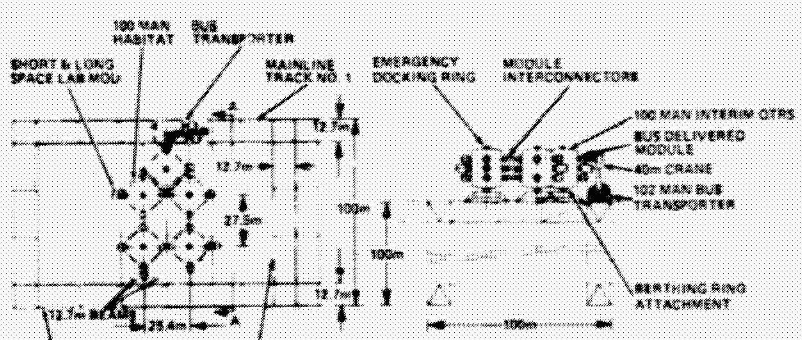

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Figure 84 Base Habitat Area – 400 People

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major sources of radiation at GEO are the geomagnetically trapped electrons and protons, galactic cosmic rays and solar flare event particles. At geostationary orbital altitudes the trapped radiation particles undergo large temporal fluctuations (diurnal and during magnetic storm activity). The types of ionizing radiation important to SPS operations include:

- Electrons and secondary radiation: bremsstrahlung (with variation of factor of two due to parking longitude location)
- Protons (flux from solar flare protons dominates) and secondary radiation protons, neutrons
- Heavy ions (HZE), secondary radiation: protons, neutrons and lighter nuclei.

Other sources of induced radiation environment should also be considered. For example, ionizing radiation due to onboard nuclear powered payloads and equipment, X-ray equipment, and possible nuclear weapon detonations.

Allowable crew radiation exposure criteria and radiation protection techniques for the GEO base are discussed below.

3.2.1 Radiation Exposure Limits

Figure 86 lists the current astronaut radiation exposure limits, as defined by the National Academy of Science/Radiobiological Advisory Panel/Committee on Space Medicine in 1970. These astronaut radiation exposure limits are based upon a 5-year career and are presently included in the STS Payload Safety Guidelines Handbook. These limits are, of course, intended to cover all forms of ionizing radiation (natural and induced). Comparable radiation exposure limits are also shown for industrial workers, as defined by the Department of Labor OSHA regulations. The low OSHA limits are also contrasted with the maximum radiation limit allowed for each Apollo mission.

It is interesting to note that the average skin dose experienced by the Apollo astronauts was very low (about 1 rem), since no solar event occurred. Nevertheless the maximum limit for Apollo was established for a program of national importance that included less than one hundred volunteer astronauts. The OSHA standards, of course, apply to millions of industrial workers. The SPS construction base is presently estimated to have approximately 800 workers on board, which equates to a 10,000 man

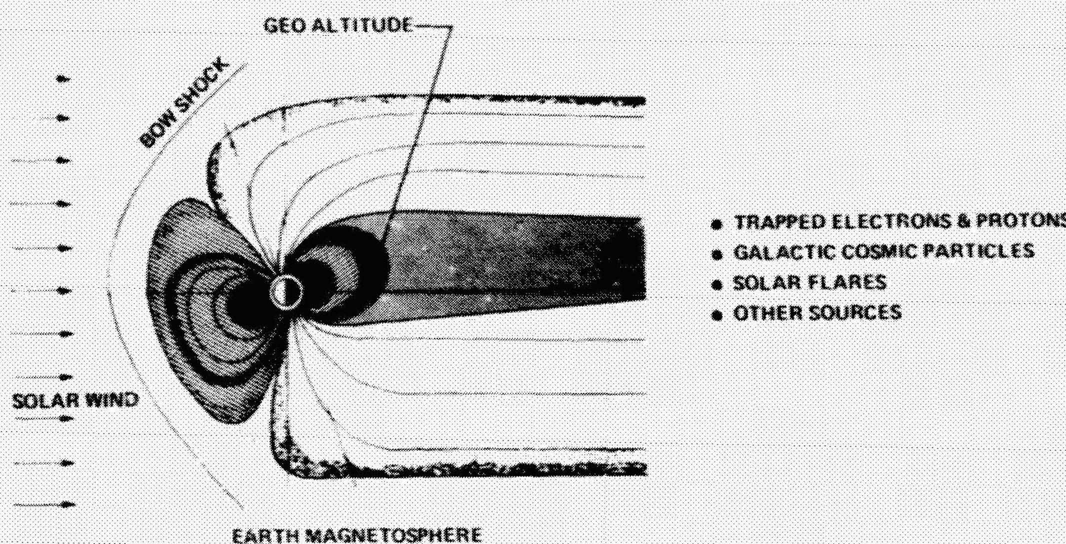

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Figure 85 SPS GEO Radiation Sources

SHOULD INDUSTRIAL LIMITS APPLY TO SPS GEO SPACE WORK FORCE

	ASTRONAUT*			INDUSTRIAL WORKER**	APOLLO MAX LIMIT
	SKIN (0.1mm)	EYES (3mm)	BONE MARROW (5cm)	BFO & EYES	BFO & SKIN
1 YR AVG DAILY RATE	.6	.3	.2		
30-DAY MAXIMUM	[illegible]	37	25		65 & 520*** PER MISSION
QUARTERLY MAXIMUM	105	52	35	3	
YEARLY MAXIMUM	225	112	75	5	
CAREER	1200 (5 yr)	600	400	235 (@ 65)	

* SPACE TRANSPORTATION SYSTEM PAYLOAD SAFETY GUIDELINES HDBK NASA/JSC · JSC 11123, JULY 1976

** FEDERAL REGULATIONS · LABOR PART 1910 OSHA · 1 JULY 1978

***APOLLO MISSIONS 7 TO 17 ONLY HAD ~ 1 REM AVG SKIN CREW DOSE SINCE NO MAJOR SOLAR PARTICLE EVENTS OCCURRED

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Figure 86 Radiation Exposure Limits & Constraints (REMS)

work force over a 30-year period. Hence, allowable SPS radiation limits may have to be established with respect to societal considerations.

3.2.2 Shielding for GEO Trapped Electrons

The average REMs that a crew member will experience each day in geosynchronous orbit is plotted as a function of equivalent aluminum cabin wall thickness, as shown in Figure 87. In order to reduce the skin dose to 1.11 REMs per day for the maximum quarterly exposure limit (i.e., 105 REMs less 5 REMs for OTV LEO/GEO transit) at least 10 mm of aluminum should be provided. Aluminum is not a very effective shield for this level of radiation due to Bremsstrahlung (secondary radiation) effects. However, by adding a thin inner layer of tantalum, the cabin radiation level can be lowered to provide a margin for other unscheduled radiation conditions (e.g., x-ray inspection, etc.). The use of compound wall design techniques is an effective way of coping with Bremsstrahlung which provides increased radiation protection for minimum shield thickness and weight. Practical shielding designs that can reduce the daily dose rate to OSHA levels require further study and remain as a technology issue.

3.2.3 Solar Flare Radiation Protection

The GEO base solar flare radiation protection system must be able to provide timely warning of a high energy solar event, so that the crew can safely reach a radiation shelter to ride out the storm. The characteristics of a typical solar event are shown in Figure 8?, together with related data on the severity and duration of prior solar events. Minimum aluminum shielding thickness requirements are provided.

Once a solar flare is observed, a 20 to 30 minute delay occurs in particle propagation before an increase in the background energy level is detected. From the onset of increased radiation, the maximum flux level may be attained within 15 minutes to a few hours according to J. Wilson et al (NASA TND 8290, 1976). However, recent communication with G. Heckman at the Boulder NOAA, Space Environment Laboratory indicates that maximum flux rise time occurs less rapidly, from 2 to 100 hours. The corresponding time delay for the first particle to arrive is about 1/3 to 1/2 of the time to reach peak intensity. The peak intensity, in turn, may last only intermittently or for a few hours and the subsequent decay period may be over in a matter of hours or days. Data from the 20th solar cycle shows that the highest event recorded lasted for five days and that a few lower energy events lasted 20 days. Hence, the radiation storm shelter must be able to support the crew life support functions for several days.

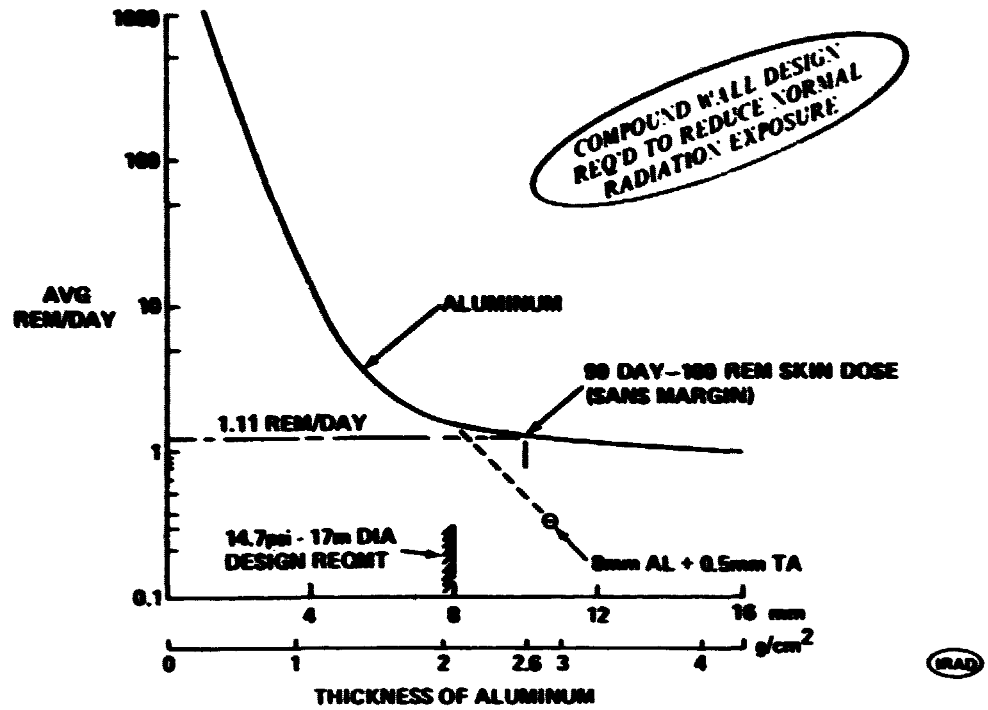

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Figure 87 Shielding Thickness for GEO Trapped Electrons Plus Bremsstrahlung (270° East Longitude)

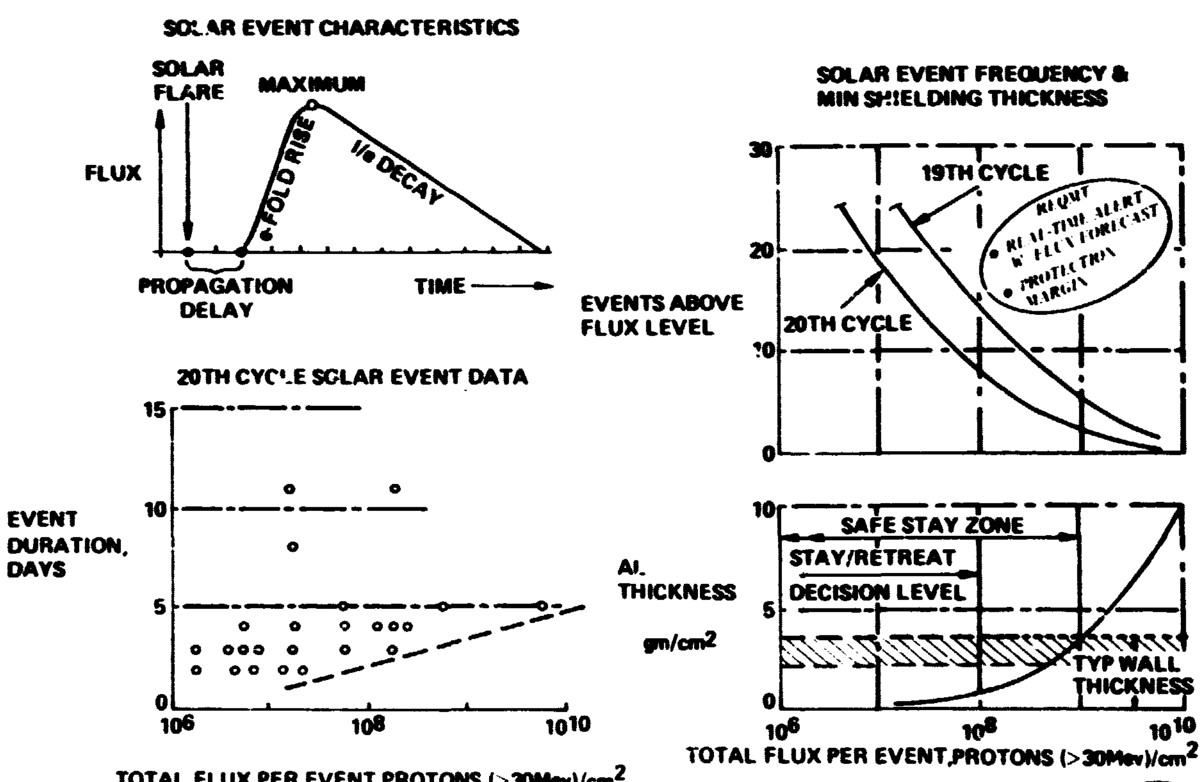

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Figure 88 Solar Flare Radiation Protection Requirements

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In the upper right part of Figure 88, the frequency of solar events is plotted as a function of the severity of the event (protons/cm^2). Smoothed historical data are shown for the two most recent solar cycles. Cycle 21 is now underway and resembles cycle 19 rather than cycle 20. The lower right-hand part of the figure shows the cabin wall thickness necessary to protect against this range of event sizes. A typical cabin wall thickness needed for shielding trapped electrons in GEO is also shown at 2.6 to 4 gm/cm^2 (i.e., 1.0 to 1.5 cm of aluminum). A 4 gm/cm^2 shield gives protection for any event up to 1×10^9 p/cm^2 flux, however, a minimum thickness of 10 gm/cm^2 is needed for a major solar event (Aug 1972) provided the crew is also equipped with personal shielding for the eyes and testes during peak exposure. Development of a real time solar flare alert system with flux forecast is needed. If the alert system can be triggered at predetermined energy levels below the nominal wall radiation protection level, then a built-in margin for error in forecasting accuracy could be achieved.

3.2.4 SPS GEO Base Radiation Design Considerations

The allowable crew dose for the SPS GEO construction base remains to be established. Total accumulated dose limits are required for the entire mission profile, that is, time in LEO, LEO/GEO transit and the GEO base. How much margin should be provided for unscheduled exposure and whether the astronaut allowed radiation levels are applicable to SPS are areas for further study, as indicated in Figure 89.

Protection against trapped electron flux in geosynchronous orbit must be factored in all aspects of GEO base operations and design, which include IVA assignments in remote work stations, free fliers, crew buses and crew habitation modules. A multi-layered cabin wall of 2.6 gm/cm^2 aluminum equivalent is recommended for the crew module as shown in the figure. The other IVA crew stations could be designed with lighter shielding provided that the total allowable dose is not exceeded. In addition, if EVA operations are needed, they should be conducted near local midnight to minimize normal belt radiation exposure. However, EVA should be avoided during large scale fluctuations due to geomagnetic disturbances. The present SPS suit must be upgraded to provide added protection for GEO EVA (i.e., between 1.5 and 4 mm equivalent aluminum.)

Protection against solar flares requires an adequate flare alert warning system that will allow all GEO base workers on remote IVA or EVA assignments to retreat to the nearest storm shelter. Means for protecting stranded workers at these remote locations need to be considered together with the systems required to implement their

rescue. The storm shelter is provided with 20 gm/cm^2 of multilayered aluminum equivalent thickness. Additional shielding benefits can be attained by placing internal equipment arrangements against the outer wall.

Protection against high energy heavy ions (HZE) requires further study. Although the dose from these HZE particles is small, it is important because of possible biological effects.

3.3 ENVIRONMENTAL CONTROL/LIFE SUPPORT SUBSYSTEM - 100 MAN HABITAT

The ECLS subsystem baselined for the SPS modules is a regenerable system with closed water and oxygen loops designed to require a minimum of expendibles. As shown in Figure 90, the atmosphere revitalization section controls cabin humidity, removes CO_2, generates O_2 from water and removes trace contaminants from the atmosphere. Two water reclamation systems are included to purify wash water and distill clean water from urine. The thermal control section removes waste heat from the cabin and electronics and then rejects it to space.

It should be noted that the system described is for a typical 100 man module using regenerable type systems. No attempt was made to perform detail trades of various concepts to perform a specific function, because this effort is more appropriately done in a later design phase and not in a systems study. The concepts described further below, therefore, are not necessarily optimum but are typical and form a baseline to determine realistic weight and costs.

3.3.1 ECLS Requirements

The system requirements are shown in Figure 91. The specific quantitative requirements (e.g., O_2 required per man hour, CO_2 production, etc.) are baselined to be the same as those specified for the Shuttle and are not repeated in the chart.

Figure 92 shows the functional breakdown of the subsystem and the specific areas covered by each section. The subsystem is divided into two general areas; Life Support and Thermal Control. Life Support covers all functions necessary to support the crew with the exception of the food supply. Thermal Control provides active temperature control and waste heat rejection for the cabin and electronics.

Figure 93 lists the hardware concepts chosen to satisfy the requirements and functional breakdown shown above. The equipment weight data presented reflects actual component manufacturers data, where it was possible to obtain. (Reference Hamilton

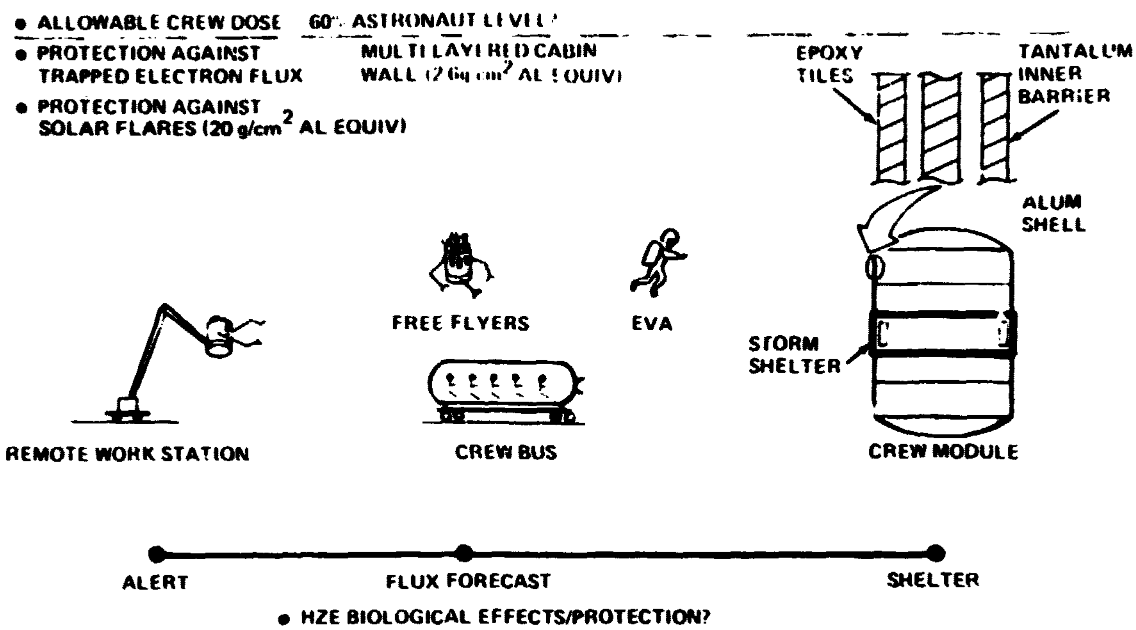
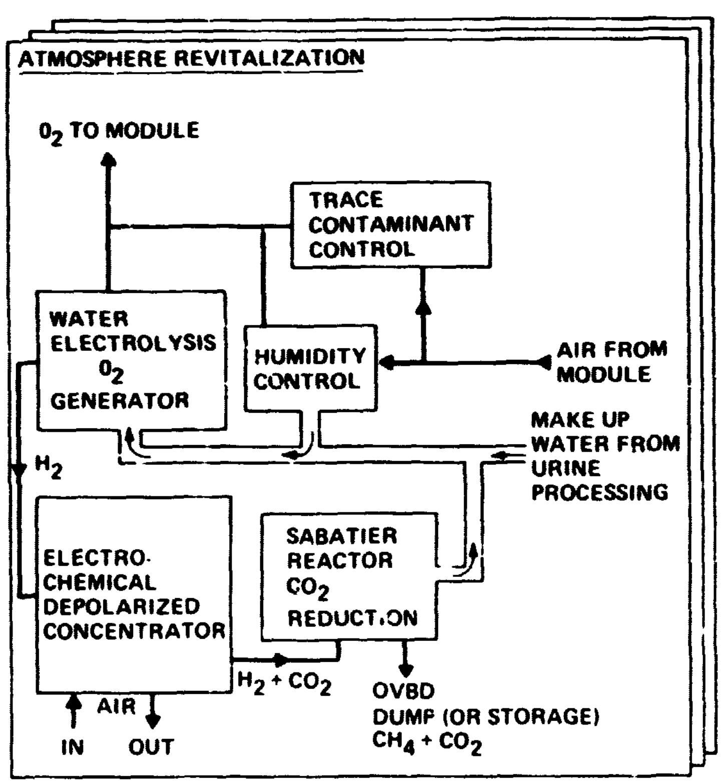


Figure 89 SPS GEO Base Radiation Design Considerations



MASS CHARACTERISTICS

ECLS ELEMENTS	MASS	RATIONALE
ATMOS REVITAL	9.8	DETAIL EST
WATER MGT	2.6	DETAIL EST
WASTE MGT	4.3	DETAIL EST
THERMAL CTL	6.1	PART EST & GUESS
TOTAL MASS 22.8 MT		

CONSUMABLES W 10% CONTINGENCY

• 90 DAY RESUPPLY	6.9MT	
– O_2 & H_2 MAKE UP	(3.4)	PREL EST
– H_2O MAKE UP	(0.4)	
– REPLACMT. PARTS	(3.1)	
• 6 WEEK EMER. SUPPLY	13.8	
– O_2 GAS	(3.4)	METABOLIC
– H_2O	(10.4)	REQ

1775-268W

Figure 90 Environmental Control/Life Support – 100 Man Habitat

LIFE SUPPORT

- REMOVAL OF METABOLIC CO_2 FROM ATMOSPHERE (100 MEN)
- RECLAMATION OF O_2 FROM CO_2
- GENERATION OF O_2 & CONTROL OF ATMOSPHERIC PRESSURE & COMPOSITION (N_2/O_2)
- REMOVAL OF TRACE CONTAMINANTS
- COLLECTION & RECLAMATION OF POTABLE WATER FROM URINE
- STERILE STORAGE & MONITORING OF QUANTITY & QUALITY OF POTABLE WATER
- COLLECTION, RECLAMATION AND STORAGE OF WASH WATER

THERMAL CONTROL

- PROVIDE ACTIVE THERMAL CONTROL FOR:
  - CABIN ATMOSPHERE
  - AIR COOLED ELECTRONICS
  - COLD PLATE COOLED ELECTRONICS
  - EXPERIMENTS/PROCESSING EQUIPMENT/MANUFACTURING, ETC.
- PROVIDE FOR REJECTION OF ALL WASTE HEAT BY USE OF ACTIVE SYSTEMS (E.G. SPACE RADIATOR)

1775-269W

Figure 91 ECLS System Requirements

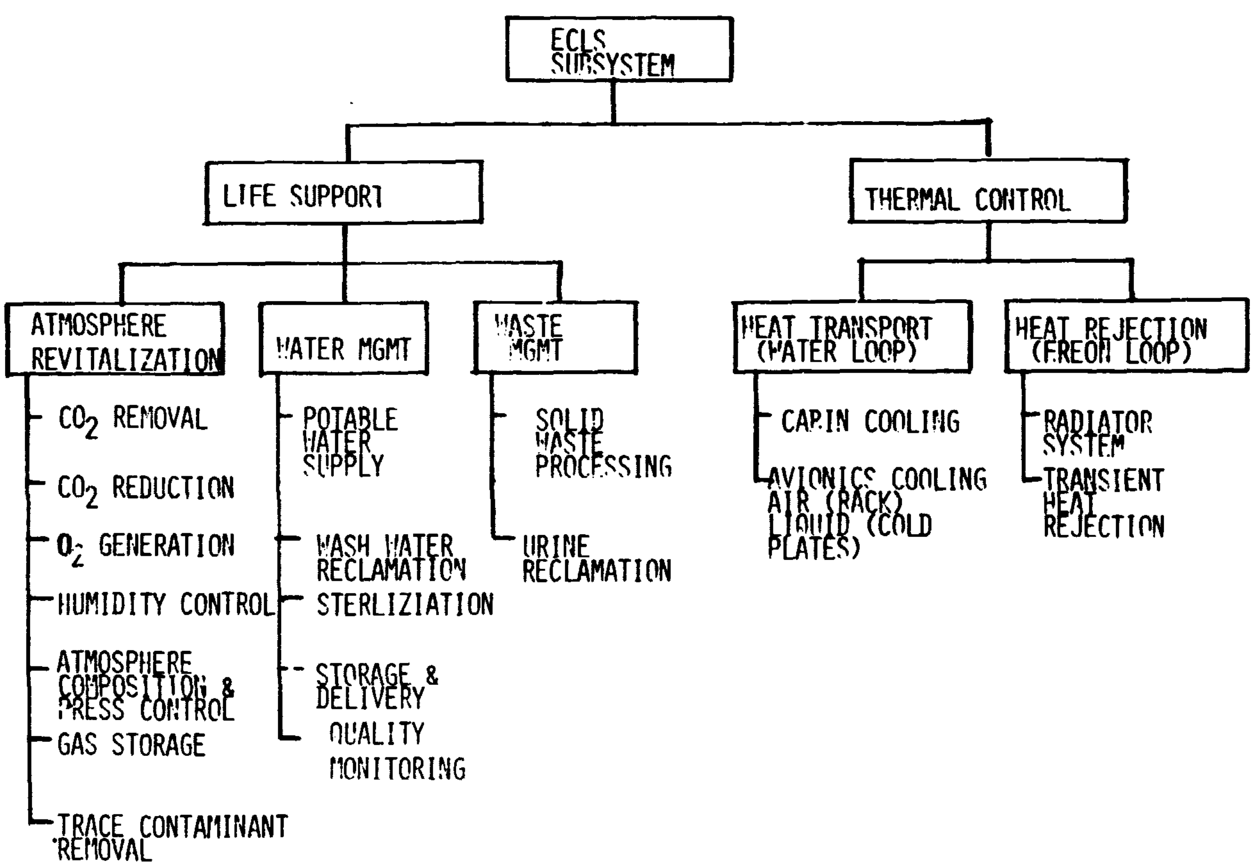


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Figure 92 ECLS Subsystem — Functional Breakdown

SECTION & FUNCTION	CONCEPT	WT. (LB)	
• ATMOSPHERE REVITALIZATION			
– CO_2 REMOVAL	ELECTROCHEMICAL DEPOLARIZE CONCENTRATOR	6000R	SINGLE SYSTEM IN USE
– CO_2 REDUCTION	SABATIER REACTOR	1000R	SINGLE SYSTEM IN USE
– O_2 GENERATION	SOLID POLYMER WATER ELECTROYSIS	3400R	SINGLE SYSTEM IN USE
– HUMIDITY CONTROL (SUPPLEMENT)	CONDENSING LIQ/AIR HEAT EX-CHANGER W/WATER SEPARATOR	1500	SINGLE SYSTEM
– ATMOSPHERE COMPOSITION & PRESSURE CONTROL	N_2/O_2 TWO GAS CONTROL SYSTEM	400R	SINGLE SYSTEM IN USE
– GAS STORAGE (N_2 TNK)	HIGH PRESSURE TANKS	7600	AS MANY TANKS AS REQ'D TO FIT IN
– TRACE CONTAMINANT REMOVAL	CATALYTIC CONVERTER, ABSORBANTS, FILTRATION	1800	SINGLE SYSTEM IN USE
• WATER MGMT			
– WATER TANK	ACCUMULATOR	500	AS MANY AS REQ'D TO FIT IN
– WASH WATER RECLAMA-TION & PROCESSING	HYPERFILTRATION (REVERSE OSMOSIS)	5000R	SINGLE SYSTEM IN USE
– STERILIZATION	IODINE INJECTION	100	4 SYSTEMS
– QUALITY MONITORING	PH MONITORING, TOC, ETC.	200	4 SYSTEMS
• WASTE MGMT			
– SOLID WASTE COLLECT & PROCESSING	VACUUM DRY (SHUTTLE TYPE)	3000	4 "BATHROOMS"
– URINE PROCESSING & RECLAMATION	VAPOR COMPRESSION DISTILLATION	6500R	SINGLE SYSTEM IN USE
• HEAT TRANSPORTS SECTION (WATER LOOP)	WATER LOOP & PUMPS, ACCUM, ETC.		
– CABIN/MODULE COOLING	LIQUID/AIR HEAT EXCHANGER/FAN	2000	EACH DECK HAS HEAT X CHANGER & FANS TO CONTROL TEMPERA-TURES
– AVIONICS COOLING – AIR COOLING – COLD PLATE	AIR/LIQUID HX/FAN CLOSED LOOP LIQUID COOLED COLD PLATES/RAILS	TBD	
• HEAT REJECTION (FREON LOOP)	PUMPED FREON LOOP SERVICING		
– RADIATOR	HX'S IN EACH MODULE	TBD	
1775-271W		39,000 LB	(17,700 KG)

Figure 93 Typical ECLS System Equipment – 100 Man Module

Std., "Parametric Data for Space Station.") Where data was not currently available, estimates were based on Grumman experience and judgment.

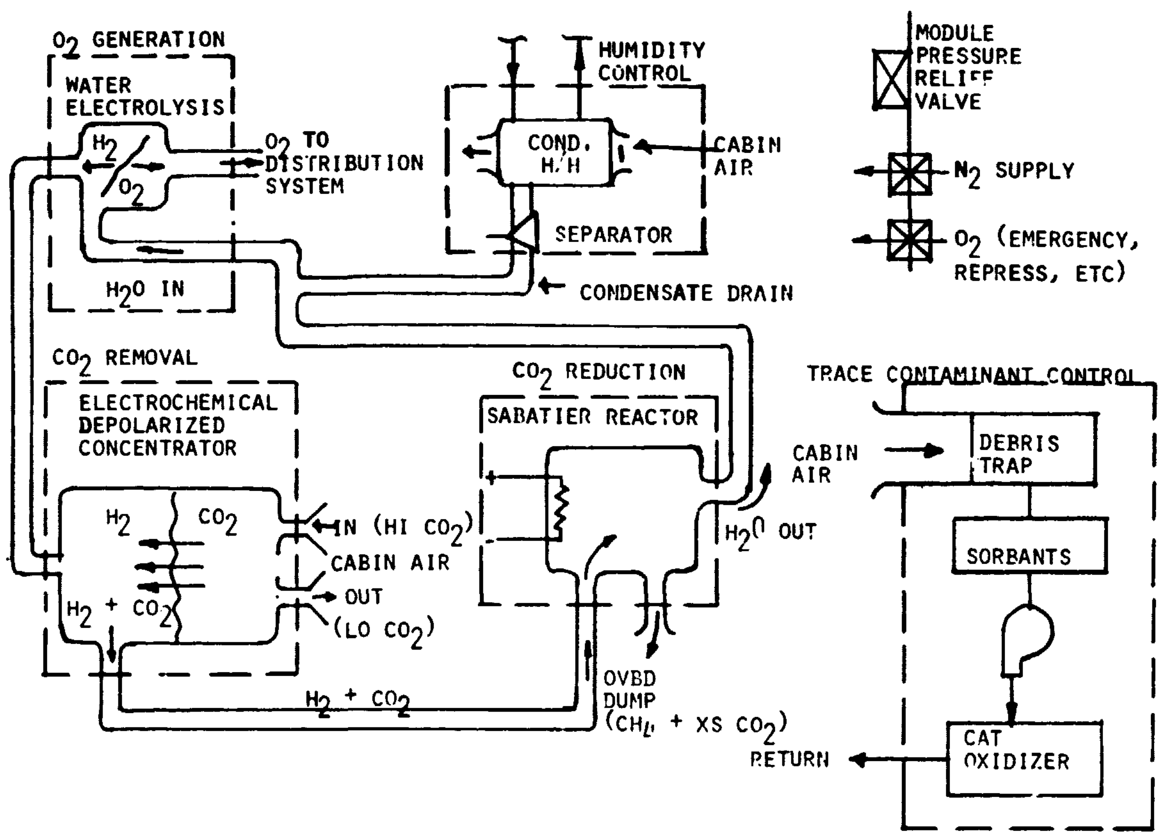
Items marked (R) in the table indicate complete built-in redundancy and are approximately double the weight of a single system. These items are considered critical to life support and a back-up must be provided, while repairs are in progress on the failed unit. All other equipments have selected built-in redundancy for historically failure prone items such as fans, pumps, controllers, etc. However, due to the extended mission times and complexity of the System, a more detailed reliability analysis should be done as the program develops.

Simplified schematics of the major sections of the ECLS subsystem are provided in Figures 94, 95, and 96. A brief description of each section follows.

3.3.2 Atmosphere Revitalization Section (Figure 94)

This section controls cabin humidity, removes CO_2, generates O_2 from water, and removes trace contaminants from the atmosphere.

- Humidity Control: Cabin air is drawn into the Humidity Control heat exchanger, where excess moisture is condensed out and removed by the water separator. The condensate is delivered to the O_2 generator, where it is electrolysed into O_2 and H_2. The O_2 is delivered back to the cabin atmosphere and the H_2 is pumped to the CO_2 Removal Section.
- CO_2 Removal: The EDC concentrates the CO_2 in the cabin air and delivers a mixture of H_2 and CO_2 to the CO_2 Reduction Unit (Sabatier Reactor)
- CO_2 Reduction: This unit combines the H_2 and CO_2 to produce water and methane (CH_4). The methane is dumped and the water is delivered to the O_2 generator to be broken down into O_2 and H_2.
- Trace Contaminant Control: Cabin air is cleaned by a combination of sorbants and catalytic oxidation.



1775-272W

Figure 94 Typical Atmosphere Revitalization Section

3.3.3 Thermal Control Section (Figure 95)

The function of the TCS is to remove waste heat from the cabin and electronics and reject it to space.

The system consists of dual water loops in the cabin and dual freon loops in the external radiator system. The water loop removes heat from the cabin air by an air to water heat exchanger in each deck. The electronics are cooled either by cold plates or, in the case of air cooled equipment, by an air/water heat exchanger.

The water loops interface with the radiator freon loop through an interface heat exchanger located external to the pressure shell to isolate the freon from the cabin.

3.3.4 Water Reclamation Systems (Figure 96)

Two different systems are used to reclaim waste water:

- Urine Recovery - This section collects, pretreats and stores urine and flush water for subsequent distillation in the VCD unit. The VCD distills the waste water and delivers the clean water to the Potable Water Tank. Iodine is injected as required to maintain sterility.
- Wash Water - Wash water is purified by a series of filtration systems with the final filtration by reverse osmosis. The purified wash water is stored in a heated tank to maintain sterility.

Figure 97 is a breakdown of the expendables and spares needed to support each 100 man module on a 90 day resupply.

The consumables/spares shown in the table reflect the weight of the limited life items actually used during the 90 days between resupply. Equipments that do not have limited life components or consumables are initially installed with spare parts and are re-supplied on an as-required basis only.

The requirement for N_2 resupply is a function of module leakage only and was estimated using shuttle leakage data and increasing it by the ratio of module surface area to shuttle surface area. The required O_2 for leakage make-up is included in the water resupply requirement.

The 6 week emergency/contingency consumables are only for oxygen and water for life support and reflect the unlikely event of total Atmosphere Revitalization Section failure. Six weeks were chosen as the contingency time limit to allow for two missed launches of the crew rotation vehicle due to weather or other unforeseen delays.

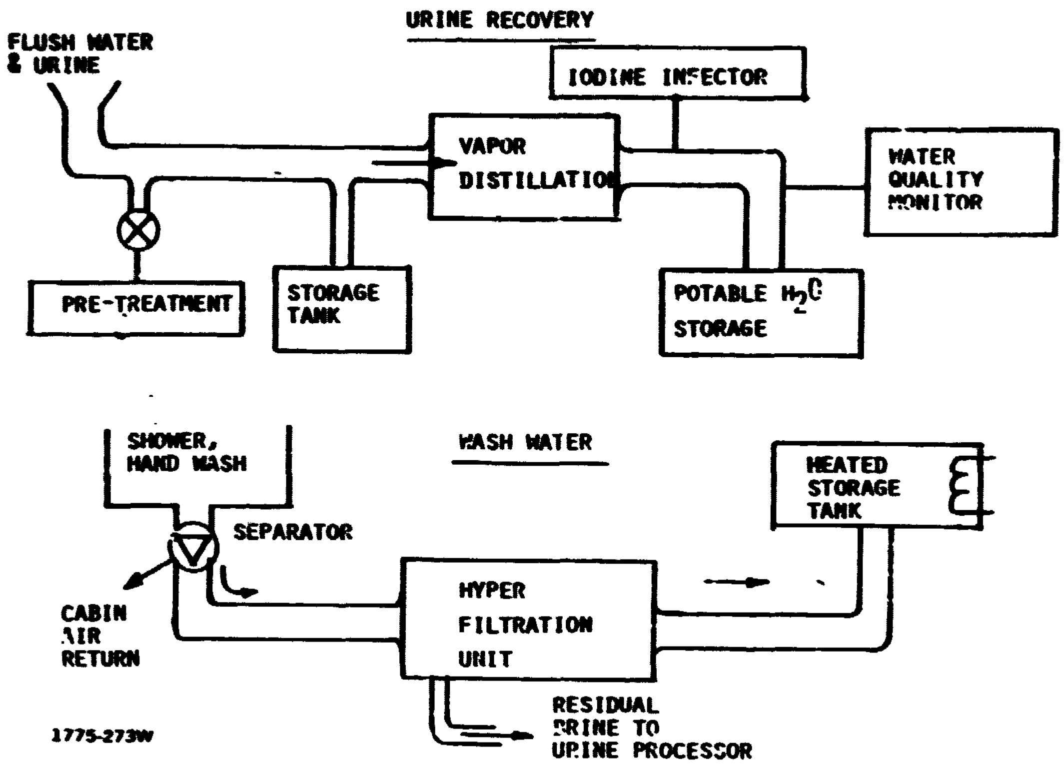


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Figure 95 Water Reclamation Systems

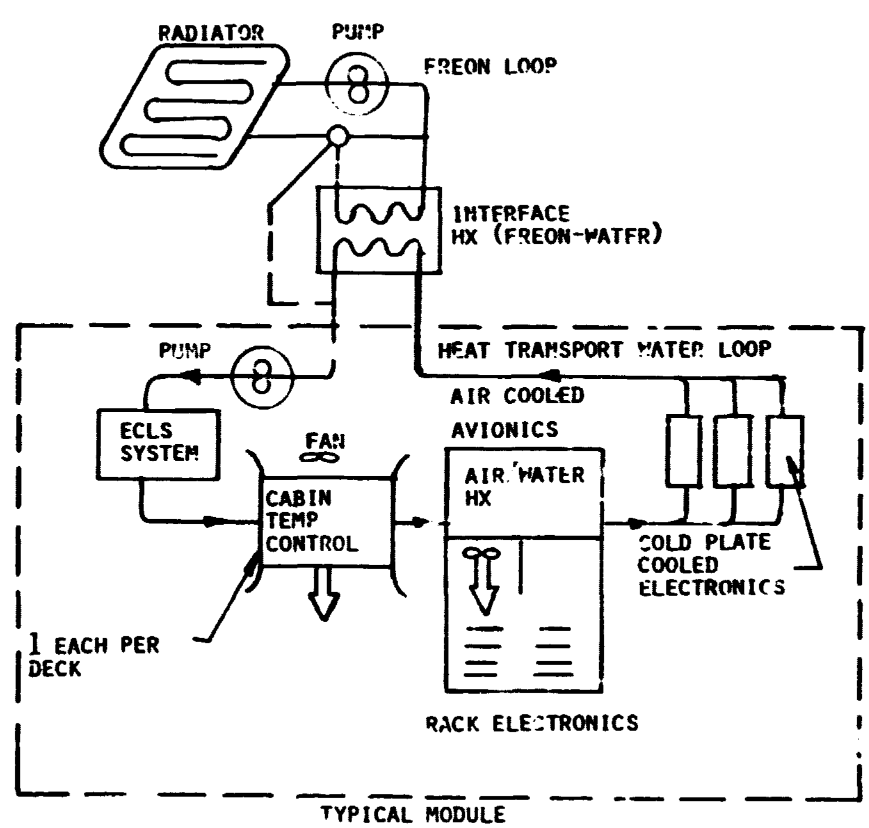

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Figure 96 Thermal Control Section

90 DAY EXPENDABLE & SPARES	MASS – LB (KG)		
CO_2 REMOVAL/EDC		110	
CO_2 REDUCTION/SABATIER		75	
O_2 GENERATION/SOLID POLYMER ELECTROLYSIS		345	
CONTAMINANT REMOVAL/CAT. OXYD., ABSORBANTS, FILTERS		800	
WASH WATER RECLAMATION/HYPERFILTRATION		1725	
WASTE MGMT/SOLID WASTE		1800	
/URINE RECL – VDC		1300	
PROCESS WATER MAKE-UP		800	
CABIN LEAKAGE MAKE-UP			
N_2 (GAS)		5000	
O_2 (1600 LBS GAS PROVIDED AS WATER)		1800	
	TOTAL	13,755 LB	(6240 KG)
SIX WEEK EMERGENCY REQUIREMENT			
O_2 (GAS)		7400 LB	(3400 KG)
WATER		23,000 LB	(10,400 KG)

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Figure 97 ECLS 90 Day Resupply/100 Man Module

As a first-cut simplification, the contingency/emergency requirement was taken to be only the life support consumables. This simplification should be studied in more detail to arrive at a more complete and possibly lighter emergency system.

The baseline system provides a starting place to investigate potential problem areas associated with constructing and operating an SPS. In particular the dumping of gases from the various process equipment (e.g., Methane from the Sabatier reactor, waste gases from the Waste Management Section, etc.) may prove to be a problem. Therefore, methods of preventing or limiting overboard gas discharge (e.g. Bosch reactor, tanks, etc.) should be investigated.

3.4 CREW MODULE MASS AND COST ESTIMATES

Figure 98 provides a summary of the current Grumman weight estimate for the SPS crew module. It shows weights for crew modules in both low earth orbit and geosynchronous orbit.

The structural weight has been estimated based on an aluminum structure of cylindrical shape 16.5 m in diameter and 17.8 m long, capable of supporting 14.7 psi internal pressure. Numerous decks divide the cylinder. Two large access/egress ports are located on either end, and 12 berthing ports are located around the circumference. Partitions and equipment mounting weights have also been estimated.

No shielding is required for LEO. A "storm shelter" approach has been used for GEO. A 7.2 m cylindrical band around the module protects one deck from solar storms. The storm shelter provides 20 grams/cm^2 shield thickness protection.

Environmental control subsystem weights are based on 100% redundant systems capable of sustaining 100 men. In addition, a weight growth/contintency factor of 33% has been maintained. All other subsystem weights remain the same as those listed in Boeings Phase 1 SPS study Final Report, Volume III Reference System Description D180-25037-3.

The lower part of Figure 98 summarizes the weight of four similar size work modules. The weight for these modules has been adjusted from Boeing's earlier report D180-24071 to reflect Grumman's estimates for habitat structure and ECLS.

Tables 7 and 8 provide a detail breakdown of the crew quarters module mass and cost data, respectively.

Table 9 lists SPS crew resupply requirements for typical crew modules and work stations on the GEO base.

HABITAT SUBSYSTEM MASS (MT)	LEO	GEO	BASIS
STRUCTURE	69.7	69.7	PREL EST
ENVIRON PROTECTION (20 g/cm^2)	0	68.3	PREL EST
ELECTRICAL POWER SUPPLY	5.0	5.0	D180-25037-3
ENVIRON CONTROL/LIFE SUPPORT	22.8	22.8	PREL EST
CREW ACCOMMODATIONS	11.0	11.0	D180-25037-3
COMMUNICATIONS/DATA HANDLING	6.0	6.0	
GUIDANCE & CONTROL	0	0	
PROP/REACTION CONTROL	0	0	
SPECIAL EQUIPMENT	0	0	
SUBTOTAL	114.5	182.8	
GROWTH/CONTINGENCY (33%)	37.8	60.3	
TOTAL DRY	152.3	243.1	

WORK MODULE STRUCTURE & ECLS UPDATED FROM D180-24071-1

OPERATION CTR	173 MT	– MISC SUPT	112 MT
– BASE MAINTENANCE	128 MT	– SPS MAINTENANCE	117 MT

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Figure 98 Crew Module & Work Module Mass Estimates

TABLE 7 CREW QUARTERS MODULE MASS & MASS BASIS

ELEMENT	MASS MT	RATIONALE	REFERENCE
STRUCTURE	69.7	GRUMMAN PREL EST	D180-25402-1
ENVIRON PROTECTION	68.3	GRUMMAN PREL EST	D180-25402-1
ELECTRICAL POWER SUPPLY	5.0	BOEING SCALED EST	D180-25037-3
ECLS	22.8	GRUMMAN ANAL	PH-2 MPR-NO 6
ATMOS REVITAL	(9.8)	DETAIL ESTIMATE	
WATER MGT	(2.6)	DETAIL ESTIMATE	
WASTE MGT	(4.3)	DETAIL ESTIMATE	
THERMAL CTL	(6.1)	PART EST & GUESS	
CREW ACCOMMODATIONS	11.0	BOEING SCALED EST	D180-25037-3
COMM/DATA HDLG	6.0	BOEING SCALED EST	D180-25037-3
GROWTH/CONTINGENCY	60.3	33%	
TOTAL	243.1 MT		

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TABLE 8 CREW QUARTERS MODULE COST DETAILS

	COST $M	SOURCE
INVESTMENT		
MANUFACTURING PLANT	(800)	GRUMMAN ESTIMATE
DELTA DDT&E	(1204)	GRUMMAN PCM
- STRUCTURE	252	
- ENVIR. PROTECT	124	
- COMM/DATA HDL	529	
- ECLS	215	
- CREW ACCOM	52	
- FUEL CELL PWR	32	
TEST UNITS	(267)	FACTOR FROM PRODUCTION
PRODUCTION HABITATS		
CONSTR MODULES (5)	1923	GRUMMAN PCM
MAINT MODULES (4 to 12)	1538 TO 4615	GRUMMAN PCM

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TABLE 9 SPS GEO BASE CREW RESUPPLY REQUIREMENTS

CREW SYSTEM	90 DAY RESUPPLY W/10% CONTINGENCY	REMARKS
• CREW HABITAT (100 MEN)	33000Kg/HABITAT	
– FOOD	17600	DRY, FROZEN & ETC. FOOD PACKAGES
– ECLS O_2 & N_2 MAKEUP	3400	HATCHES, WINDOWS, VENTS & OTHER PENETRATION LEAKAGE
H_2O MAKEUP	400	FILTRATION LOSSES
REPLACEMENT PARTS	3100	LIFE LIMITED FILTERS, ETC.
– HOUSEKEEPING ITEMS	2460	REUSABLE CLOTHING, LINENS, UTENSILS, ETC.
– OTHER CREW SUPPLIES	2100	GAMES, BOOKS, ETC. (MSC-04425, MAY 71)
– OTHER SUBSYSTEM PARTS	440	2%, PWR SUPPLY, COMM/DATA, LIGHTING, ETC.
– PACKAGING (TANKAGE, RACKS, ETC.)	3500	30% LESS FOOD
• OPERATIONS CENTER, TRAINING CENTER & MEDICAL CENTER	8920Kg/CENTER	
– ECLS O_2 & N_2 & PARTS	6500	AS ABOVE
– OTHER SUBSYSTEM PARTS	440	
– PACKAGING	2080	
• MAINTENANCE MODULE	13450Kg/MODULE	
– ECLS O_2 & N_2 MAKEUP	6800	TWICE CREW HABITAT LEAKAGE
REPLACEMENT PARTS	2170	70% OF HABITAT CREW
SPECIAL EQUIP. SPARES	930	30% OF CREW HABITAT ECLS SPARES
– OTHER SUBSYSTEM PARTS	510	
– PACKAGING		
• MANNED REMOTE WORK STATION (1 MAN)	695Kg/MRWS	– 2 MEN BRIEF OCCUPANCY
– ECLS O_2 & N_2 MAKEUP	520	LEAKAGE & TWO WEEKLY REPRESSURIZATIONS
– SPARE PARTS	15	10% ALL NONSTRUCT SUBSYS
– PACKAGING	160	30%
• CREW BUS		
– ECLS O_2 & N_2 MAKEUP	320	– HATCH LEAKAGE (W/O REPRESSURIZATION)
– SPARE PARTS	SCALE CREW SIZE TO MRWS REQUIREMENTS	
– PACKAGING		

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4 - GEO BASE BUILDUP CONCEPT

A concept for building the SPS GEO Base was developed at the very end of the Phase 2 effort.

Figure 99 illustrates a mini-construction base which can be used to assemble large space structures such as the SPS GEO Base. This facility (Mini Base) uses the end builder construction concept which is tailored to the 100m-square cross-section of the GEO base structural members. Four dedicated semi-fixed 7.5m beam machines fabricate the longitudinal members and two 7.5m mobile beam machines fabricate the lateral. vertical and diagonal members of the GEO Base structural assembly. The mini-base facility provides a track system for mobile indexers, winches and crane cherry pickers. The two mobile winches, indexers and turntable tracks allow the facility to reorient itself and index about any and all sides of the structure it has fabricated. The 120m crane cherry picker is used to assemble those structural joints which are beyond the reach of the mobile cherry pickers.

Future SPS studies should include further definition of the GEO Base Buildup concept, specific areas to be addressed are as follows:

- Expand GEO Base Buildup operations definition (assembly sequence, timelines, man power utilization and equipment requirements)
- Establish mass and cost data for major system elements of Mini Base (work facilities, flight control, electrical power and crew facilities)
- Develop Mini-Base assembly and LEO-GEO transfer concept.

4.1 MINI-BASE CONFIGURATION

The general arrangement for the mini base facility is shown in Figure 100. This facility configuration consists of a 150 m wide by 250 m high tower mounted on a 400 m by 350 m platform. 50 m square structural frames are used to construct the facility: these frames are assembled from 7.5m triangular beams.

The tower houses four fixed beam machines which are arranged to provide the longitudinal members of the 100 meter square structure to be fabricated. Two mobile beam machines and four cherry pickers, used for assembly of the structure,

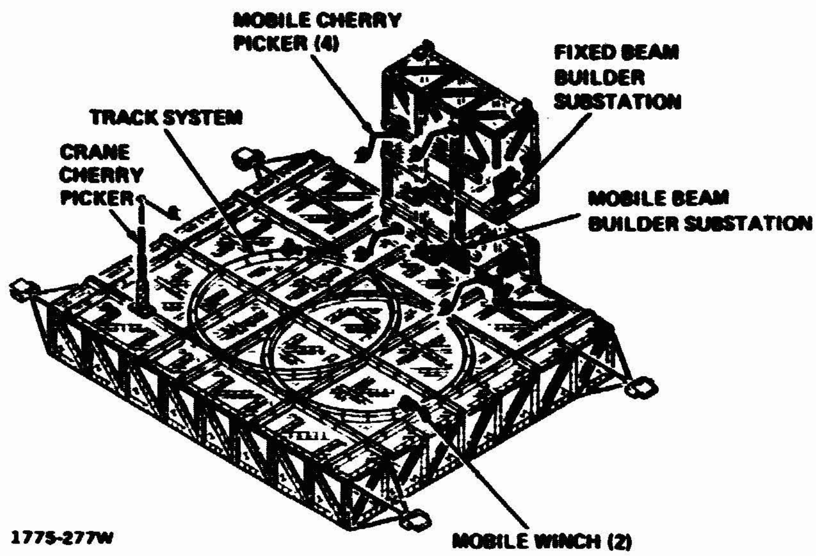

Figure 99 Facility Concept for Building GEO Base

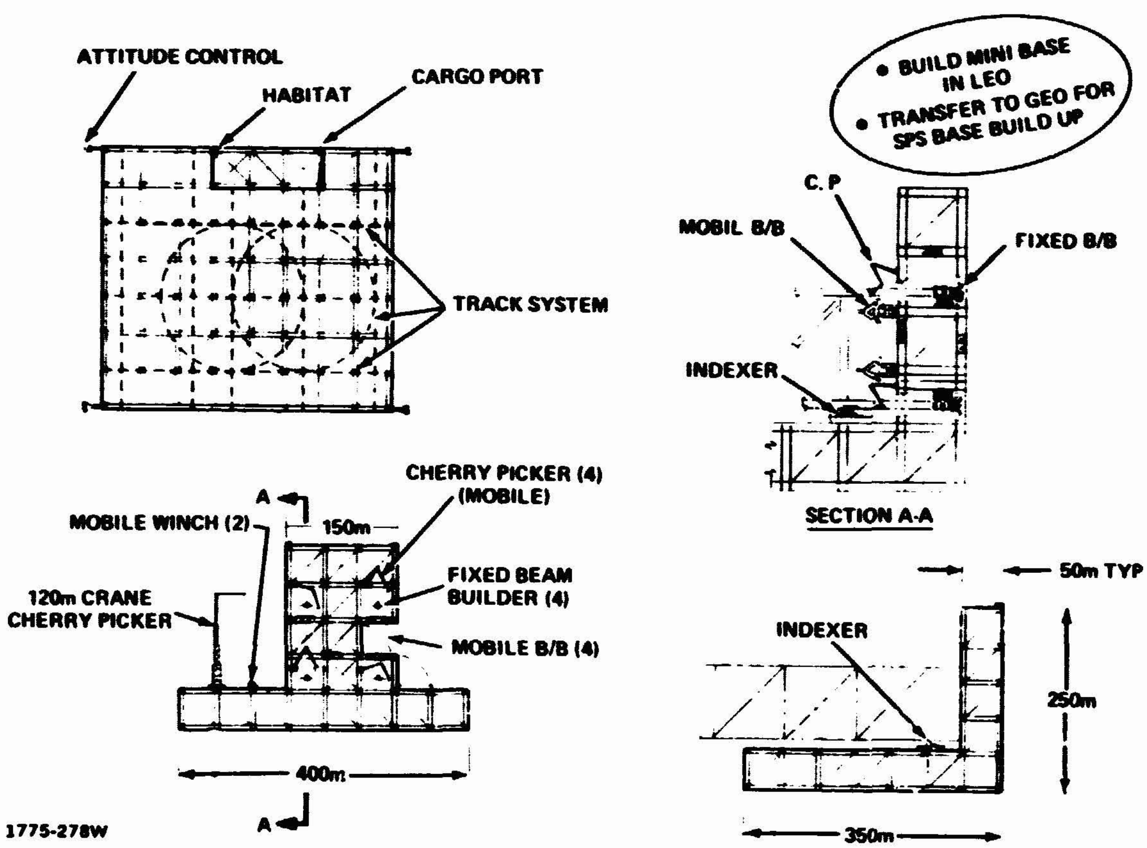

Figure 100 Facility for Building SPS GEO Base

ride a track system on the tower. Crew habitats and a cargo port are located on the upper level of the tower.

The platform provides support for the attitude control system, a track system for the mobile winches, indexers and crane cherry picker.

This mini base can be assembled in LEO and transferred to GEO for subsequent SPS base buildup.

4.2 GEO BASE BUILDUP SEQUENCE

Figure 101 illustrates a construction scenario for the assembly of the SPS GEO base. Two mini-bases, are shown in this construction sequence.

Construction operations begin with the assembly of the vertical grid for the GEO Base Solar Collector Factory. Mini-base No. 1 fabricates a 700 m long structural member. Mini-base No. 2 maneuvers into position, docks and attaches to this member via its indexer track system. Then, it begins the fabrication of the GEO base upper horizontal member at level J, while mini-base No. 1 re-orients and initiates the fabrication of the lower horizontal member. For the next vertical member, mini-base No. 2 re-orients and fabricates a 500 m member and mini-base No. 1 interrupts fabrication of the lower member to allow the cherry pickers to attach the vertical member to it. When the joint is completed, mini-base No. 2 again re-orients and both mini-bases resume fabrication of the horizontal members. This process is repeated until the entire vertical grid is completed. Then, mini-base No. 1 starts construction of the lower horizontal structural grid and mini-base No. 2 completes the overhang of the vertical structure.

After completion of the energy conversion system construction facility, the antenna construction facility is assembled. When approximately three quarters of the antenna platform is assembled, mini-base No. 2 is anchored to the platform, as shown, and used as the antenna assembly factory of the GEO base. Mini-base No. 1 completes the platform construction and then is indexed over to the vertical wall of the GEO base and used as the yoke/rotary joint factory.

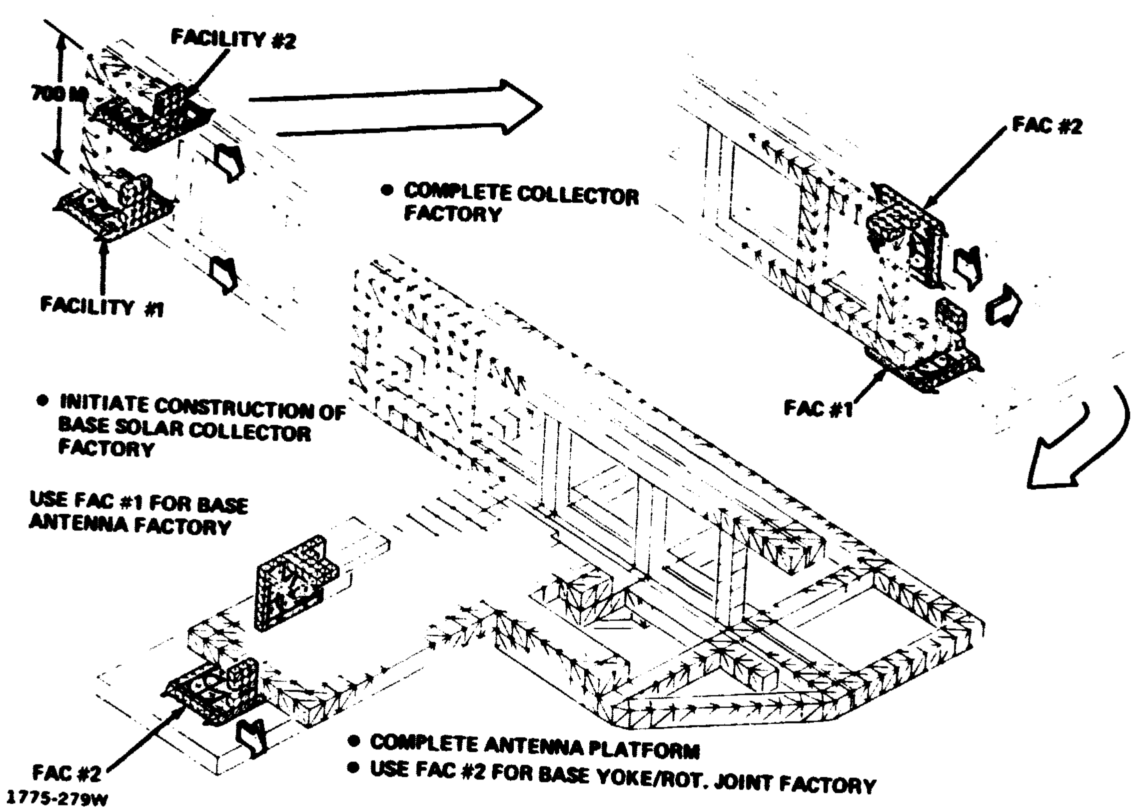

Figure 101 GEO Base Buildup Sequence

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5 - GENERAL REFERENCES

1. "Statement of Work for Grumman Aerospace Corporation on Solar Power Satellite System Definition Study"; Boeing Aerospace Company P.O. N-520080-9114, June 26, 1978 (Rev. 2-26-79).

2. "Solar Power Satellite System Definition Study, Part III, Preferred Concept Definition"; Boeing Aerospace Company Report D180-24071-1, March 1978.

3. "Solar Power Satellite System Definition Study Monthly Progress Reports Contract NAS9-15196", Second Report (February 4, 1977), Fourth Report (April 8, 1977) and Thirteenth Report (February 7, 1978); Boeing Aerospace Company.

4. "Solar Power Satellite System Definition Study Phase I Final Report, Volume II Phase I System Analysis and Tradeoffs (March 1, 1979); Volume III Reference System Description (April 1, 1979); Volume VI Phase I Final Briefing: Space Construction and Transportation"; Boeing Aerospace Company Reports D180-25037-2/-3/-6.

5. "Satellite Power System Concept Development and Evaluation Program"; U.S. Department of Energy and National Aeronautics and Space Administration, DOE/ER-0023, October 1978.

6. Solar Power Satellite System Definition Study Monthly Progress Reports for Boeing; Grumman Aerospace Corporation Reports NSS-SPS-B-RP001 to RP003, RP005, RP006 RP009 to RP012, RP014 and RP015, dated 14 August 1978 through 10 September 1979.

7. Solar Power Satellite System Definition Study Phase I Reports for Boeing, Phase I Mid Term Briefing (October 19, 1978), Phase I Final Briefing (December 14 and 15 1978), and Phase I Final Report (December 18, 1978); Grumman Aerospace Corporation Documents NSS-SPS-B-RP004, -RP007, and RP008.

8. Solar Power Satellite System Definition Study Phase 2 Briefings for Boeing: Phase 2 Mid Term Review (June 27, 1979) and Phase 2 Final Briefing (October 23, 1979); Grumman Aerospace Corporation Documents NSS-SPS-B-RP013 and -RP016.

9. "Space Fabrication Demonstration System, Final Report"; Grumman Aerospace Corporation Report NSS-SFDS-RP012, March 15, 1979.

10. "Space Construction Automated Fabrication Experiment Definition Study Part III Final Briefing"; Convair Division of General Dynamics CASD-ASP78-014, April 24, 1979.

11. "Space-Based Solar Power Conversion and Delivery Systems Study Final Report, Volume II Engineering Analysis of Orbital Systems"; Grumman Aerospace Company, March 1977.

12. "Space Station System Analysis Study Final Report (Part 3) Volume I Technical Report" (27 July 1977), and "Volume 5 Power System Technical Report" (31 August 1977); Grumman Aerospace Corporation Reports NSS-SS-RP021 and 025.

13. "Manned Remote Work Station Development Article Final Report Volume I Book I Flight Article Requirements"; Grumman Aerospace Corporation Report NSS-MR-RP008, March 1, 1979.

14. Hull, W.; "Life Sciences Guideline Data For Long Duration Missions"; NASA/JSC Draft Report.

15. "Life Sciences Systems Technology Development Plan"; NASA/JSC Draft Report.

16. Fraser, T.M.; "The Intangibles of Habitability During Long Duration Space Missions"; NASA Report CR-1084, June 1968.

17. "Space Transportation System Safety Guidelines Handbook"; NASA/JSC Report JSC 11123, July 1976.

18. Rysavy, G. and Council, C.; "Architecture and Environment; Basic Tools of Habitability of Space Station Design"; AIAA Paper No. 71-879, August 1971.

19. "Shuttle Orbiter Passenger Compartment Habitability Requirements Study For Flight Personnel Accommodations"; NASA MSC Report MSC-04425, May 1971.

20. "Thermal Control and Life Support Subsystems - Parametric Data for Space Station"; prepared under the Regenerative Life Support Evaluation Program (Contract NAS9-14782) Hamilton Standard, March 1977.

21. "Habitability Data Handbook - Volume 4 Food Management"; NASA/MSC Report MSC03903.

22. Kline, R.L., "Space Station Habitability Issues"; AIAA/MSFC Symposium on Space Industrialization, May 26 & 27 1976.

23. "Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems"; Radiobiological Advisory Panel Committee on Space Medicine, National Academy of Sciences, 1970.

24. Wilson, J., and Dunn F.M.; "Preliminary Analysis of the Implications of Natural Radiations on Geostationary Operations"; NASA TND-8290, September 1976.

25. King, J. "Solar Proton Fluences for 1977-1983 Space Missions"; Journal of Spacecraft and Rockets Vol II, No. 6, June 1974.

26. Rossi, M.L. and Stanber, M.O., "Radiation Protection Design Considerations for Man in Geosynchronous Orbits"; IEEE meeting, Washington D.C., July 1977.

SUPPRESSED TRAJECTORY INVESTIGATION

The original HLLV reference trajectory provided an injection to a 110 km x 477 km transfer at 100 km altitude. Studies of potential upper atmosphere effects at Los Alamos Scientific Laboratories indicated concern regarding depletion of ions in the ionosphere as a result of hydrogen and water molecules from the HLLV upper stage rocket engines. There has also been some discussion of the possibility of formation of noctilucent clouds at 80-85 km. These have occasionally been observed after rocket launches.

It is thought that suppression of the HLLV trajectory below 100 km will minimize ionosphere effects. Suppressed trajectories such as the one developed during Phase I of the present study and illustrated in Figure 1, with injection at 85 km, may increase the likelihood of noctilucent clouds. Because of this latter possibility, although it is presently unclear whether these clouds, even if they form, would have any environmental impact, a further trajectory suppression study was undertaken to explore the possibility of flying trajectories that never exceed 70-75 km.

The investigation began with a relatively unconstrained trajectory with injection at 70 km. This trajectory is illustrated in Figures 2, 3, and 4. The peak second stage altitude is about 100 km. Max q slightly exceeds (700 psf) and the second stage angle of attack ranges from 10 to 20 degrees. Q at injection reaches about (50 psf), indicating some heating. The main problem with this trajectory is post-injection drag loss. Figure 4 shows the instantaneous apogee versus time. At injection, it increases rapidly to the desired 477 km, but drag losses reduce it to about 250 km.

This problem can be reduced by injecting at a positive path angle rather than the customary zero-degree Hohmann transfer injection. The transfer orbit then has a perigee of less than the injection altitude. The orbit and injection parameters may be computed as a function of perigee altitude, as shown in Figures 5 and 6.

From these curves, injection conditions were selected for path angles of one and two degrees, leading to suppressed trajectories No. 2 and No. 3 shown in Figures 7 through 11. The increased path angle helps in three ways: (1) Post-injection losses are reduced (not plotted for No. 3, but apogee decrease after injection was only about 20 km; (2) angle of attack at high heating is increased; (3) peak altitude for the optimal trajectory is reduced.

Trajectories No. 1, No. ', and No. 3 are all optimal for the assigned injection conditions. Computed payload capability was about 3% less than the global optimum trajectory (the optimal trajectory with optimal injection conditions). These trajectories were computed without lift; the vehicle characteristics table included only a drag table. This is a common practice for normal ascent trajectories where lift is not important but it is incorrect for these suppressed trajectories. Trajectory No. 4 (Figures 12, 13, and 14) was computed with the appropriate lift and drag tables for the second stage. The ·imple targeting algorithm used in this trajectory routine does not correct for second tage lift; as a result the injection path angle increases to 2.5 degrees and the transfer c. bit apogee is too high. This slight error is not important to the analysis of suppression.

The peak altitude of No. 4 is still too high, being nearly 90 km. Achieving the desired trajectory suppression requires a non-optimal boost trajectory. Trajectories No. 5 and No. 6 were computed with boost suppression. No. 5 was not plotted; No. 6 achieves the desired degree of suppression as shown in Figures 15 and 16.

The payload loss due to suppression is about 7%. A JSC trajectory similar to No. 6 included a deeper dip into the atmosphere before injection and exhibited severe heating. Trajectory No. 6 has a maximum high-mach dynamic pressure of (70 psf); the heating is comparable to entry heating.

Trajectory No. 6 is recommended as an interim alternate reference trajectory. At such time as further HLLV study work is done, a more sophisiticated trajectory program (POST) should be used to optimize the suppressed trajectory subject to the appropriate dynamic pressure, angle of attack, and altitude constraints.

Pertinent statistics for trajectory No. 6 are given in Table 1.

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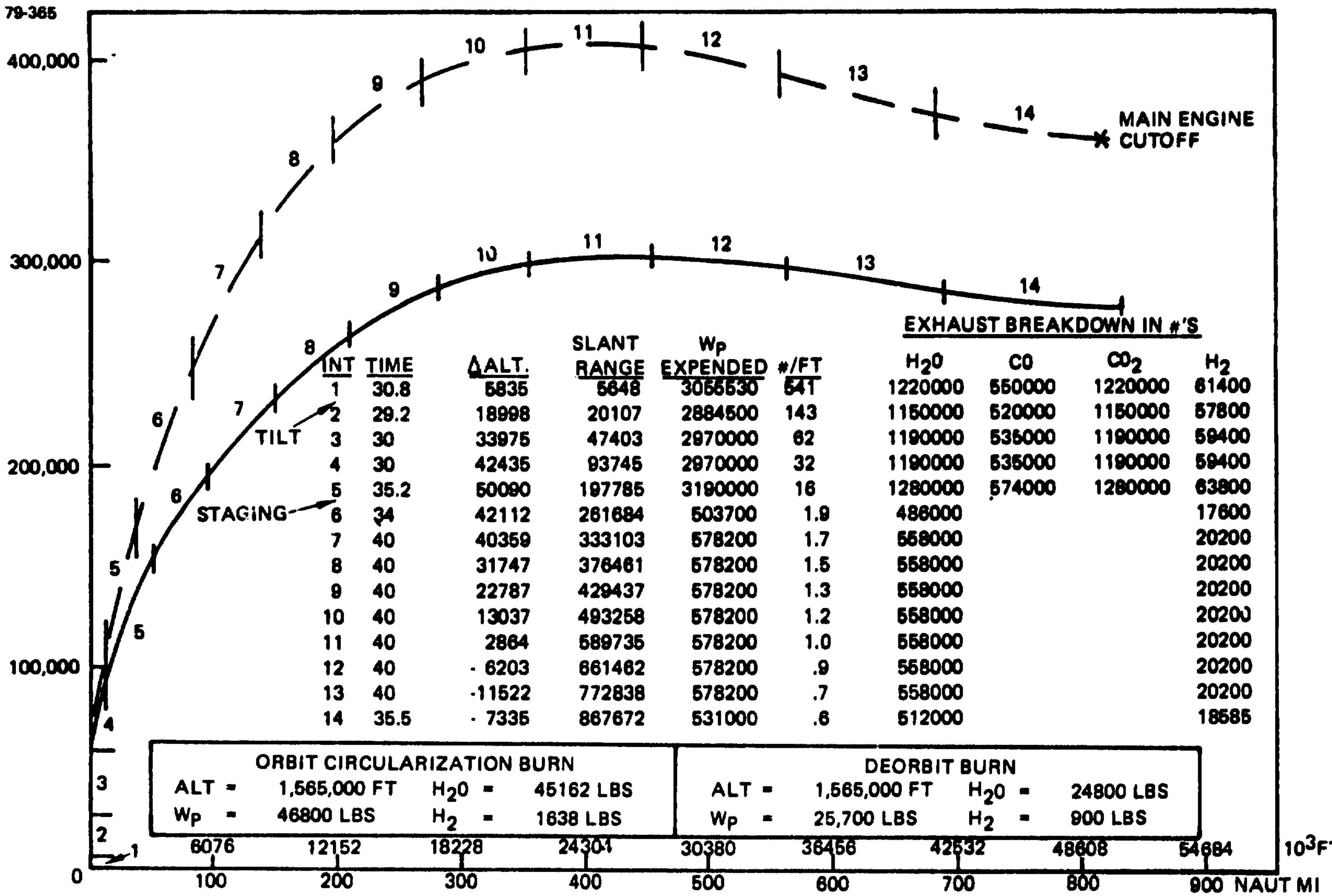
BOEING SPS

FIGURE 1

SPS Heavy Lift Launch Vehicle Trajectory and Exhaust Products Data



						EXHAUST BREAKDOWN IN #'S			
INT	TIME	ΔALT.	SLANT RANGE	W_P EXPENDED	#/FT	H_2O	CO	CO_2	H_2
1	30.8	5835	5648	3055530	541	1220000	550000	1220000	61400
2	29.2	18998	20107	2884500	143	1150000	520000	1150000	57800
3	30	33975	47403	2970000	62	1190000	535000	1190000	59400
4	30	42435	93745	2970000	32	1190000	535000	1190000	59400
5	35.2	50090	197785	3190000	16	1280000	574000	1280000	63800
6	34	42112	261684	503700	1.9	486000			17600
7	40	40359	333103	578200	1.7	558000			20200
8	40	31747	376461	578200	1.5	558000			20200
9	40	22787	429437	578200	1.3	558000			20200
10	40	13037	493258	578200	1.2	558000			20200
11	40	2864	589735	578200	1.0	558000			20200
12	40	- 6203	661462	578200	.9	558000			20200
13	40	-11522	772838	578200	.7	558000			20200
14	35.5	- 7335	867672	531000	.6	512000			18585

ORBIT CIRCULARIZATION BURN	DEORBIT BURN
ALT = 1,565,000 FT H_2O = 45162 LBS	ALT = 1,565,000 FT H_2O = 24800 LBS
W_P = 46800 LBS H_2 = 1638 LBS	W_P = 25,700 LBS H_2 = 900 LBS

ALTERNATE TRAJECTORIES CAN BE CONSIDERED WITH LOWER INSERTION ALTITUDES IF ENVIRONMENTAL CONSIDERATIONS DEEM NECESSARY

FIGURE 2 HLLV SUPPRESSED #1

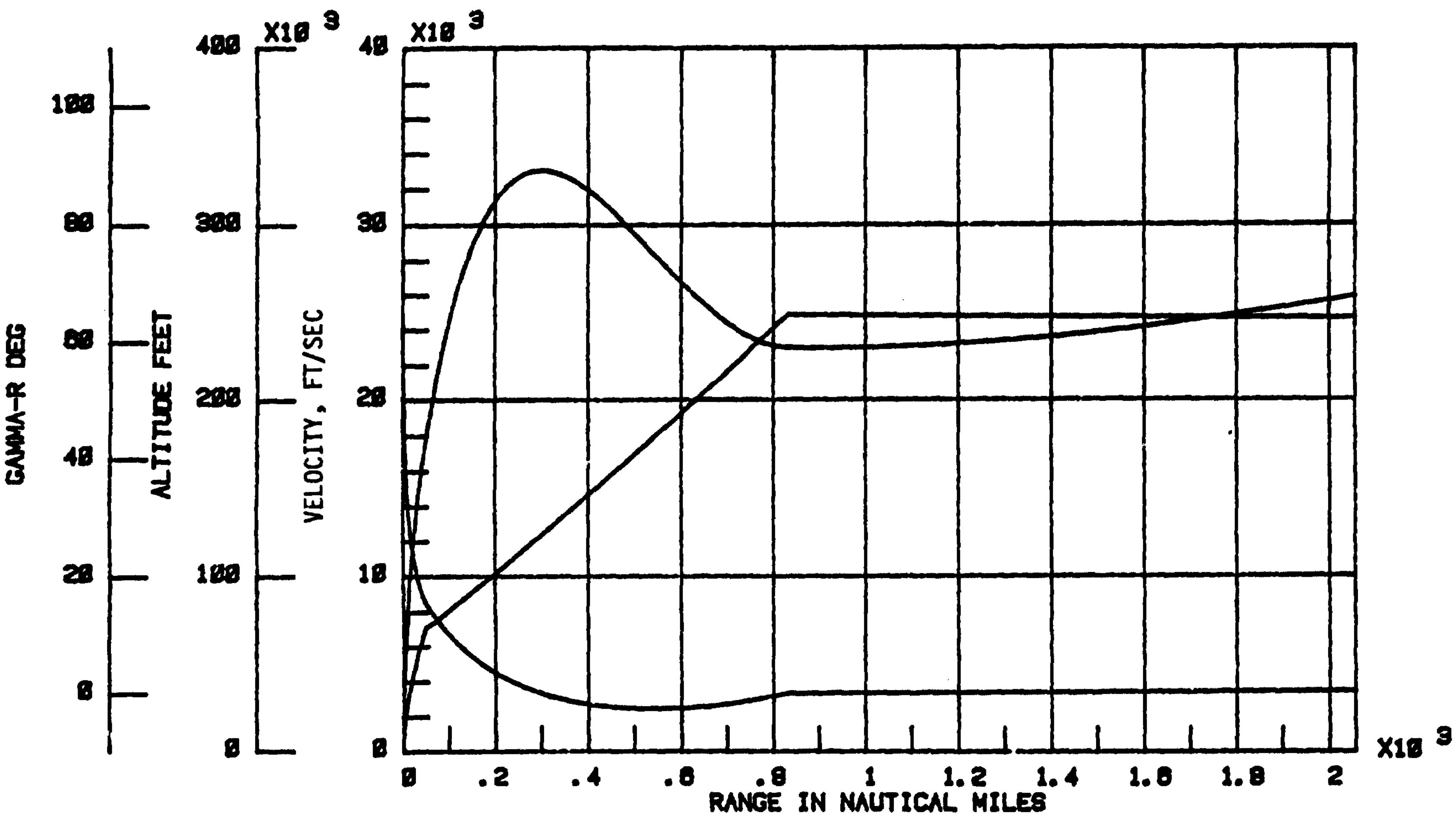


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FIGURE 3 HLLV SUPPRESSED #1

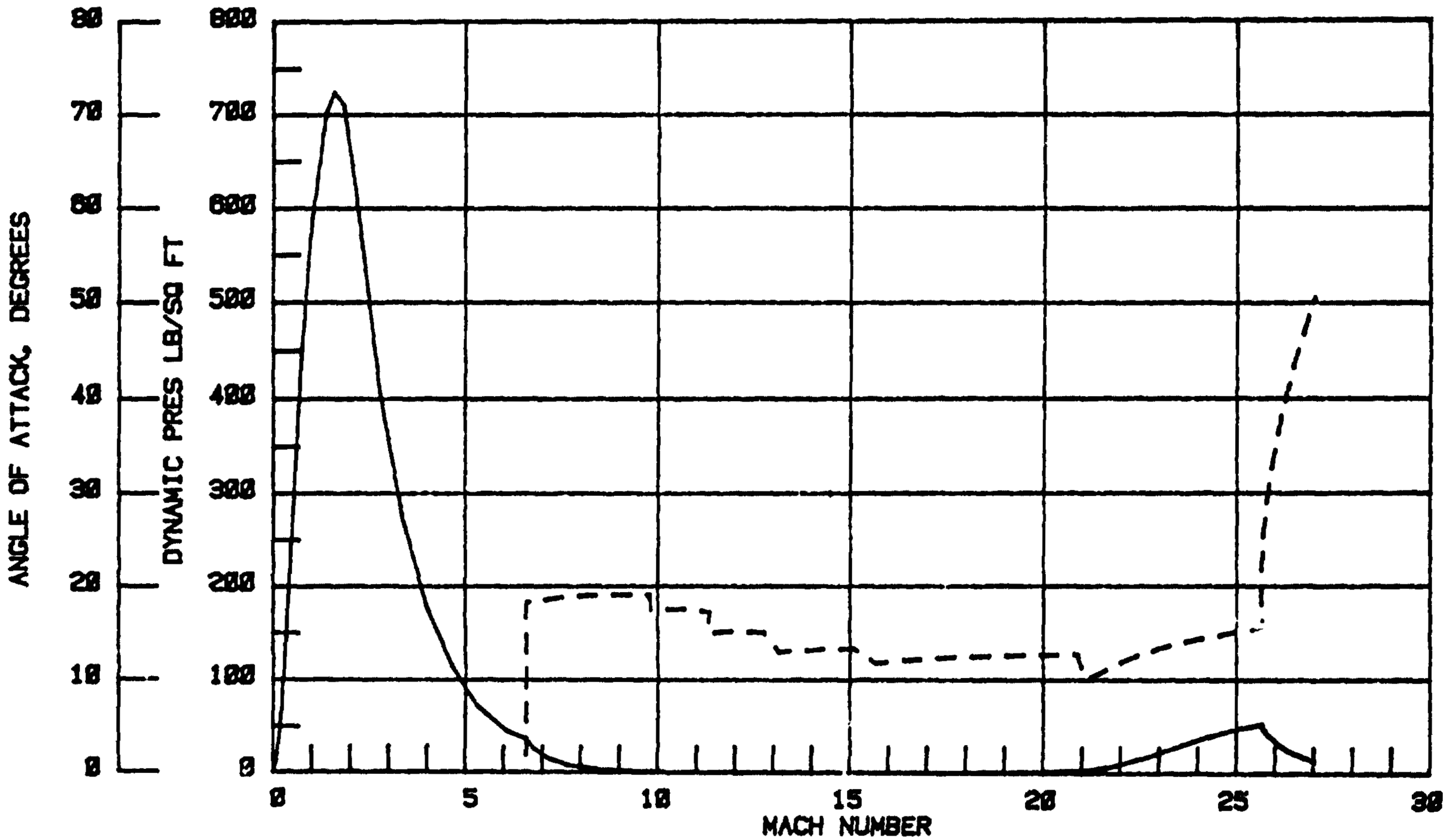

FIGURE 4 HLLV SUPPRESSED # 1

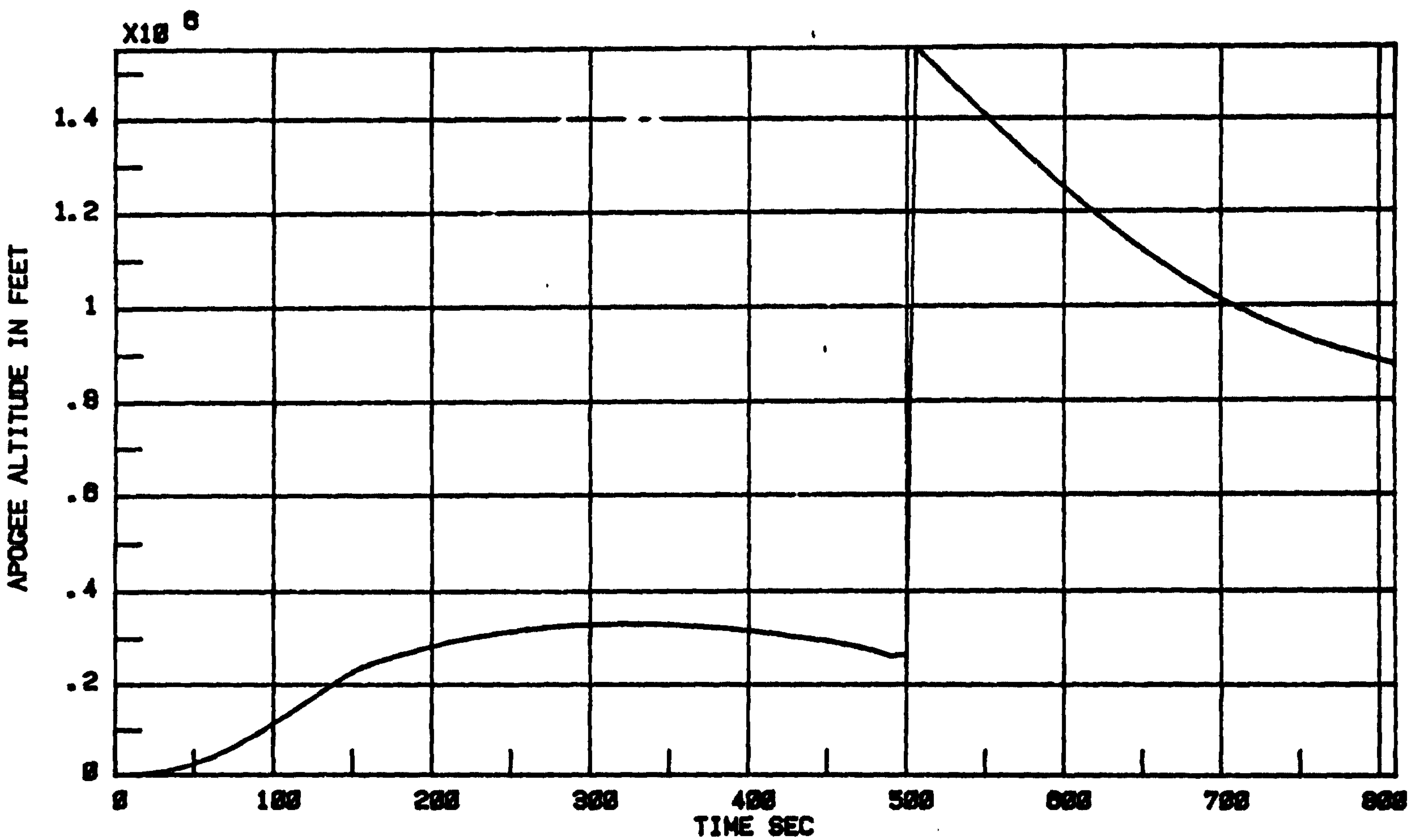

FIGURE 5 INJECTION PARAMETERS @ H=70 KM

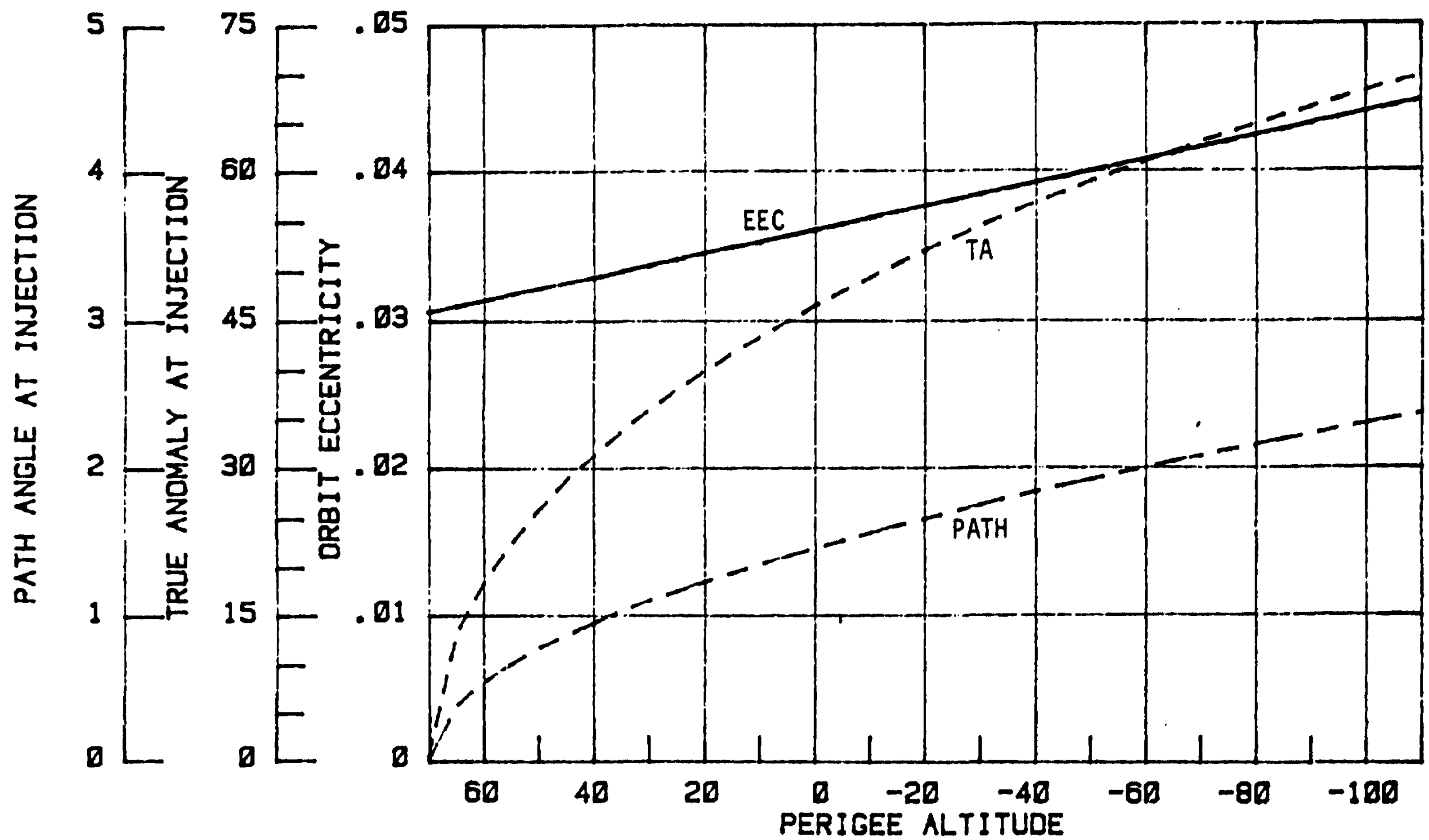

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FIGURE 6 INJECTION PARAMETERS @ H=70 KM

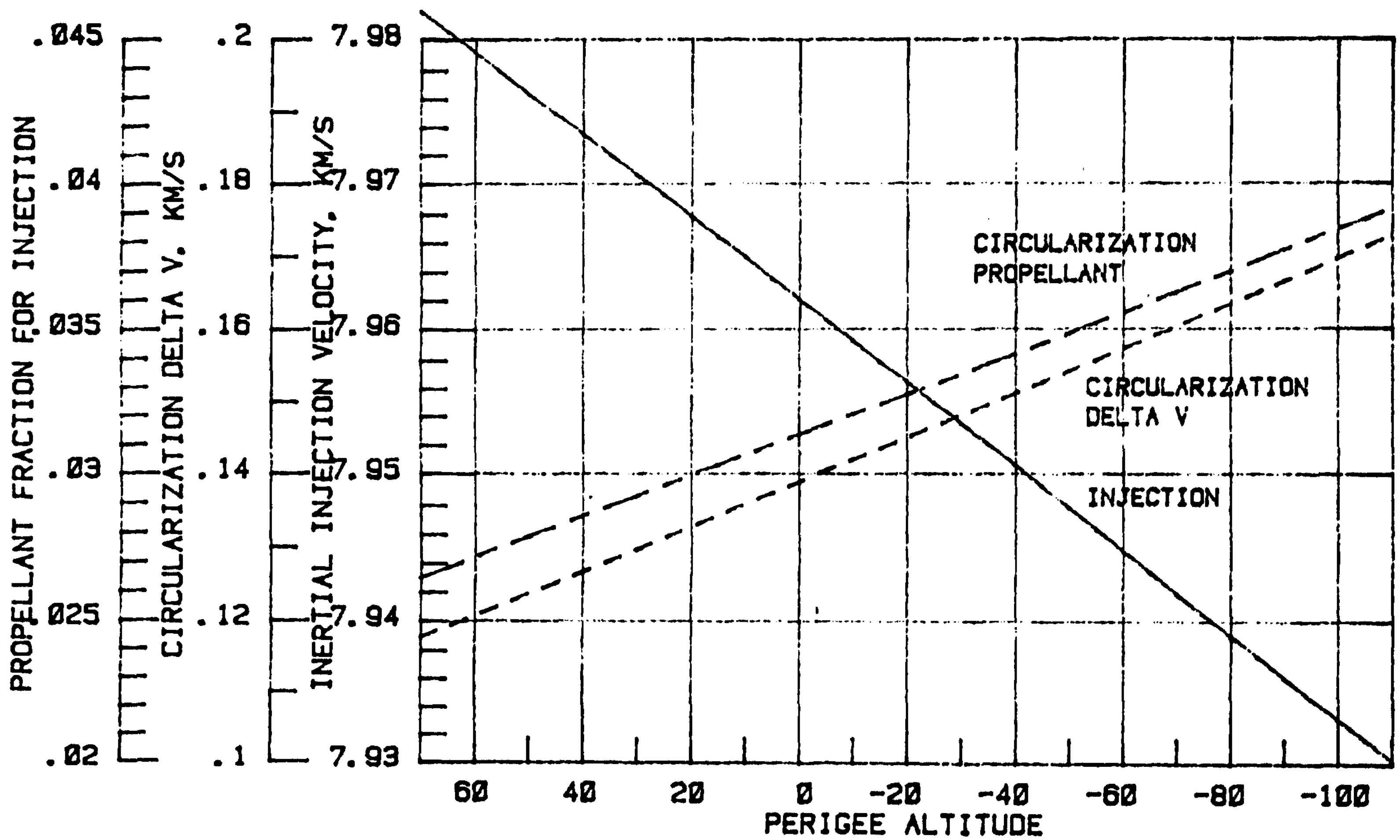

FIGURE 7 HLLV SUPPRESSED #2

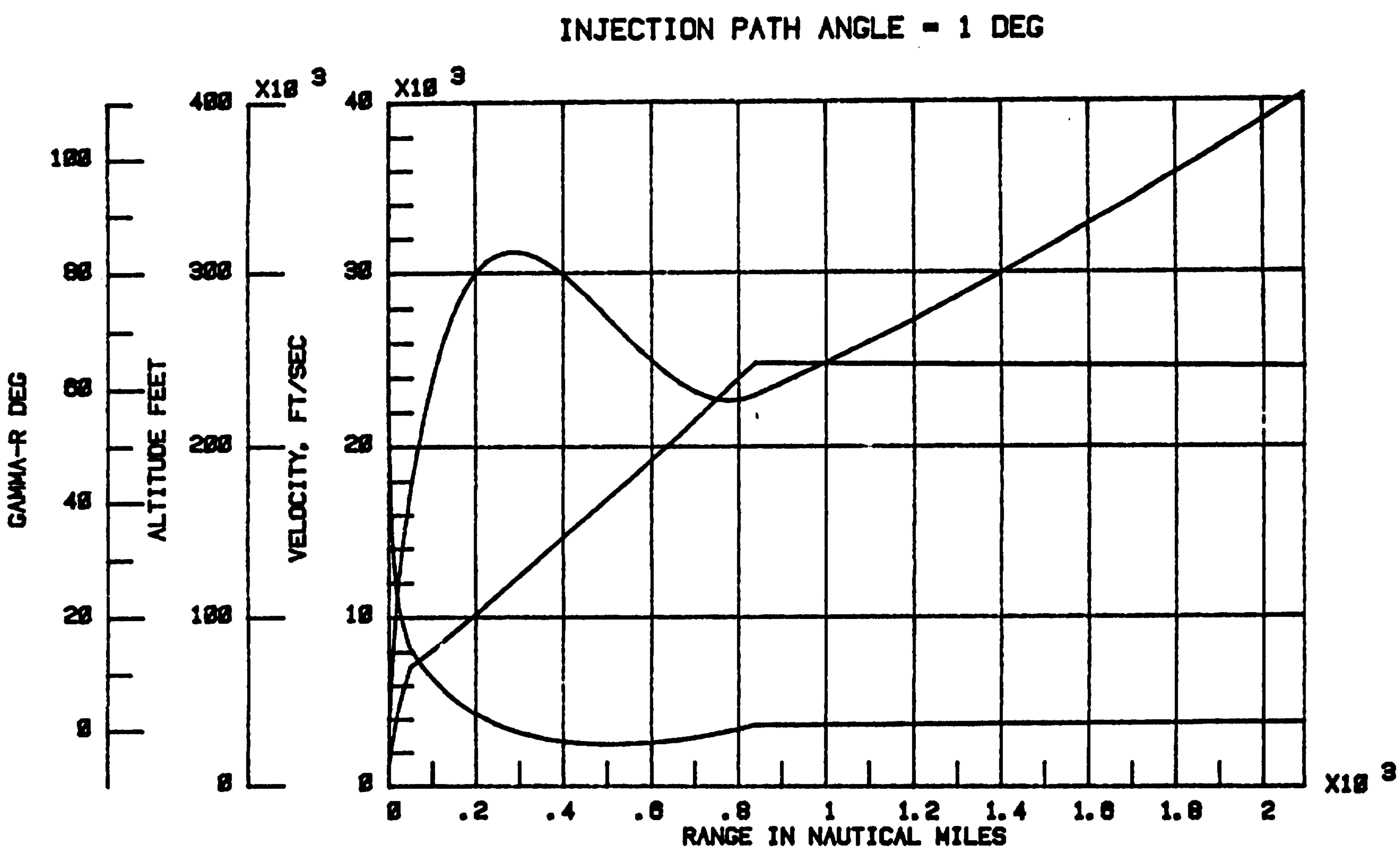

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FIGURE 8 HLLV SUPPRESSED #2

INJECTION PATH ANGLE = 1 DEG

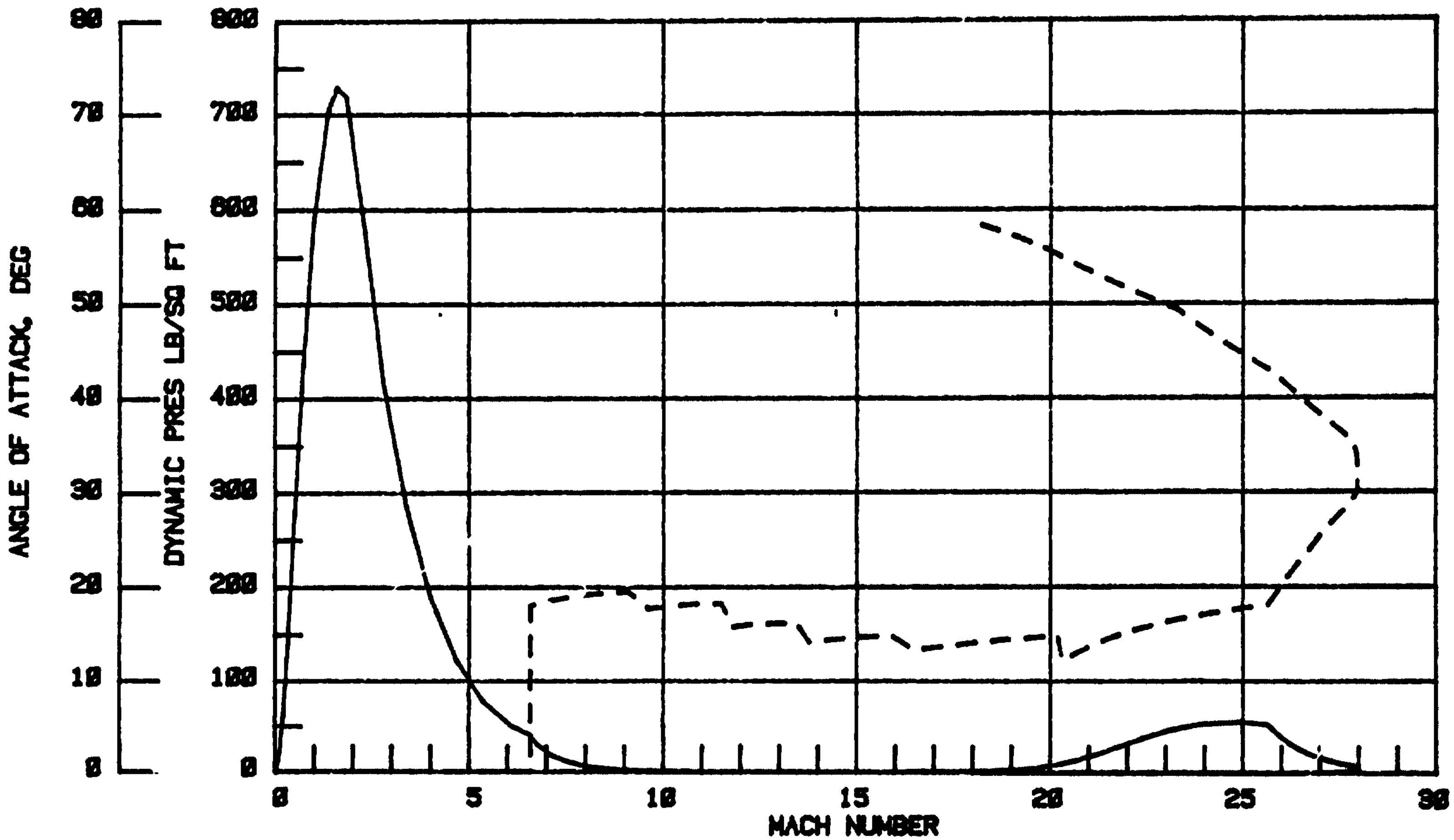

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FIGURE 9 HLLV SUPPRESSED #2

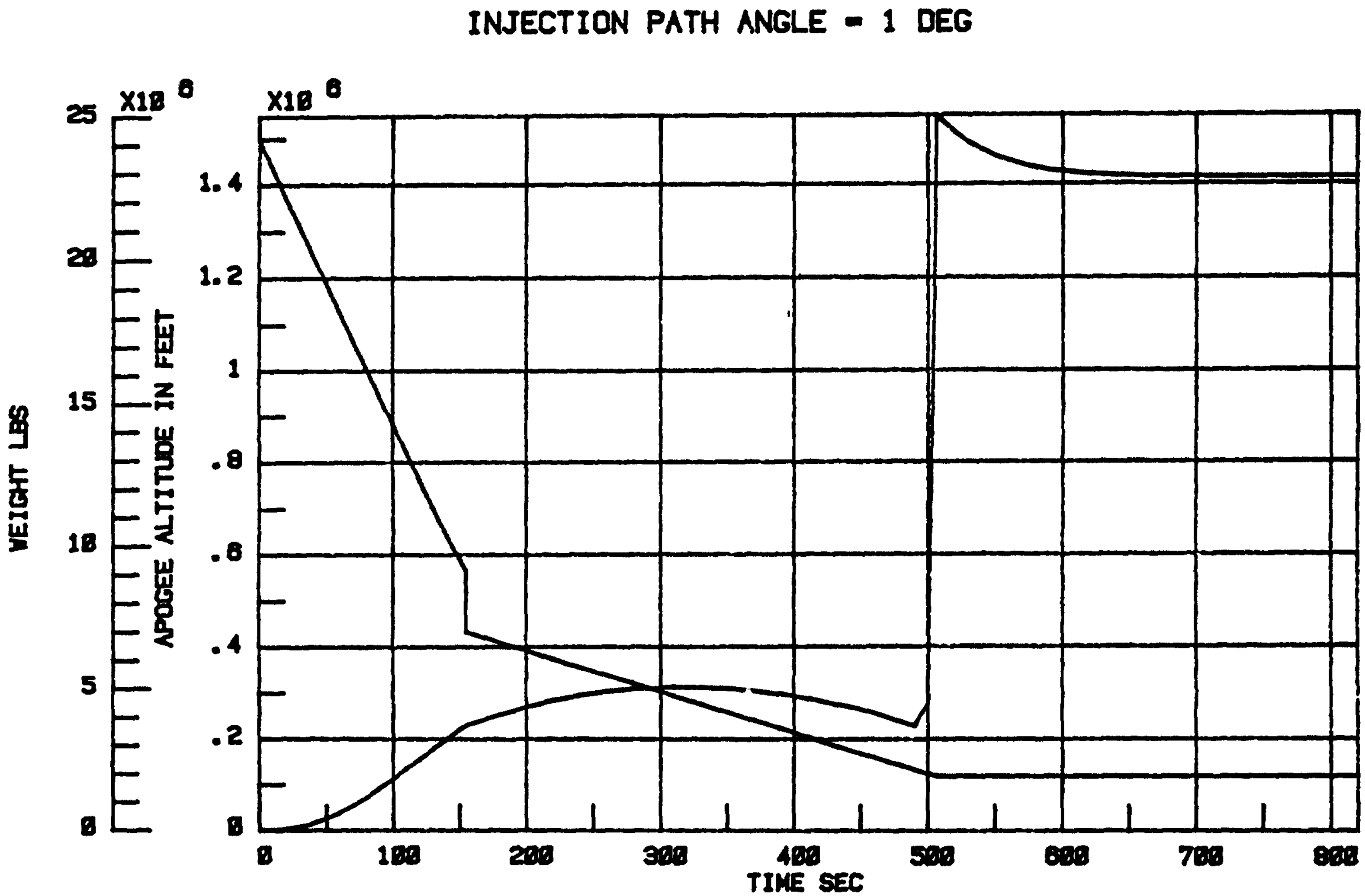

FIGURE 10 HLLV SUPPRESSED #3

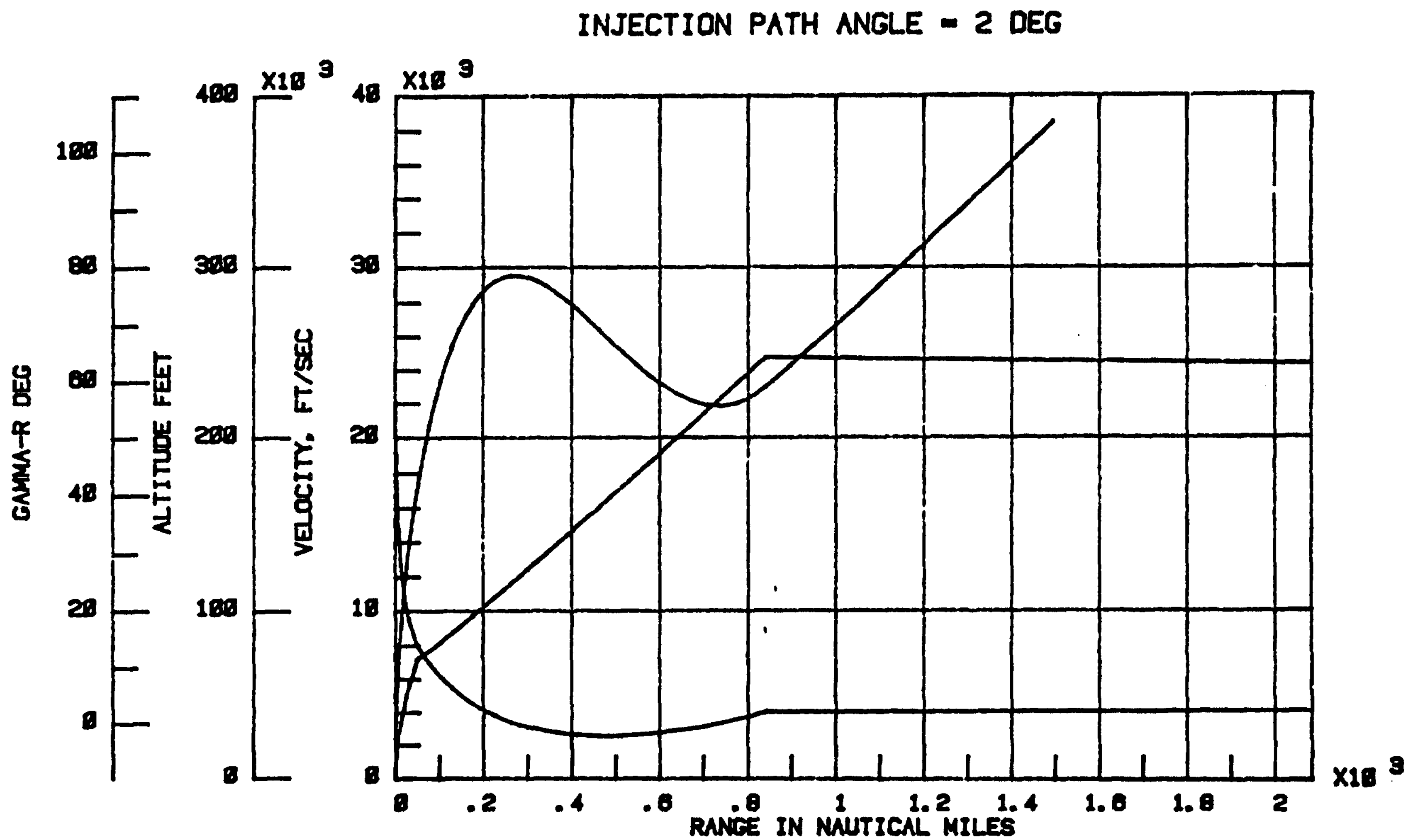

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FIGURE 11 HLLV SUPPRESSED #3

INJECTION PATH ANGLE = 2 DEG

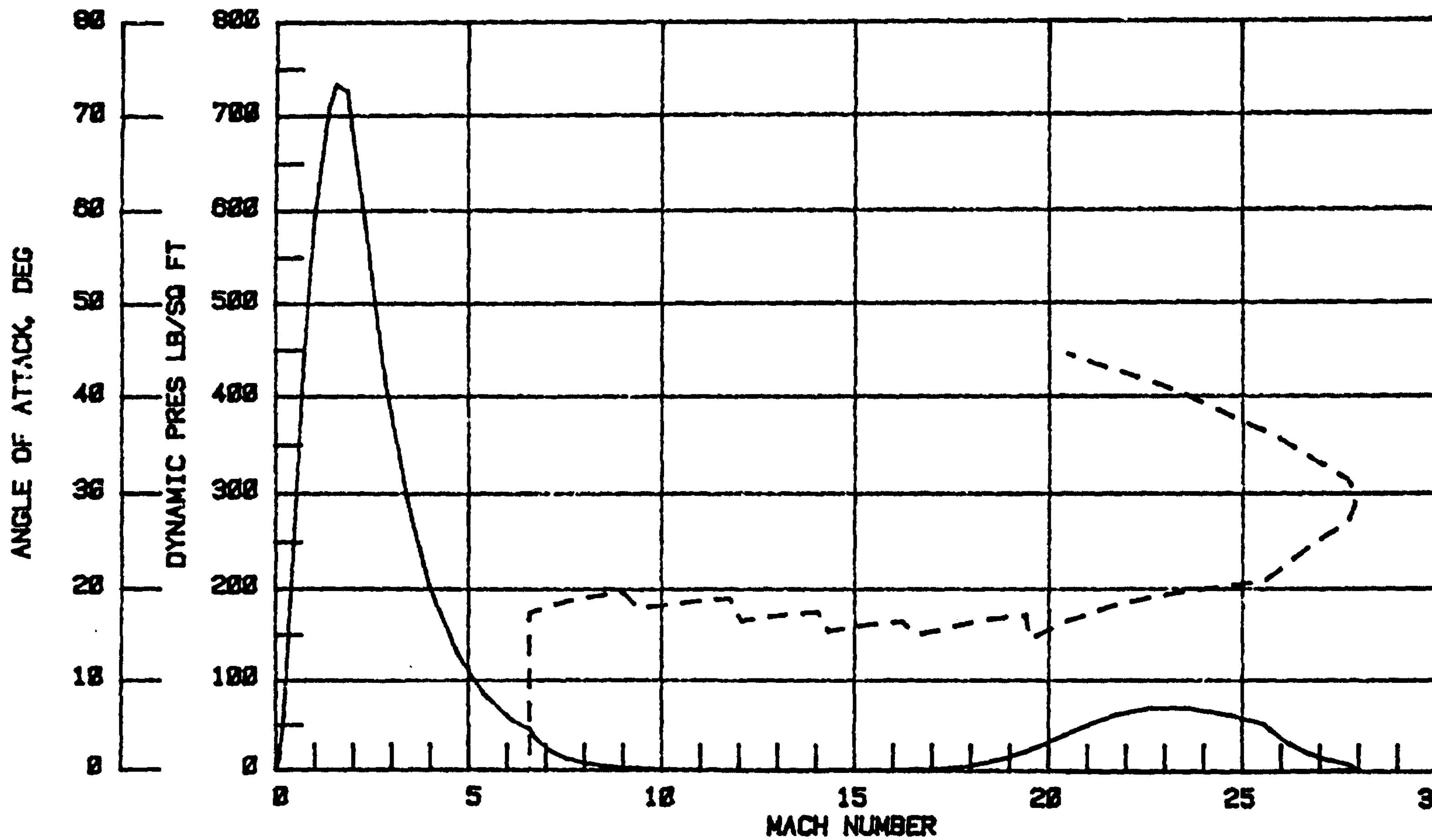
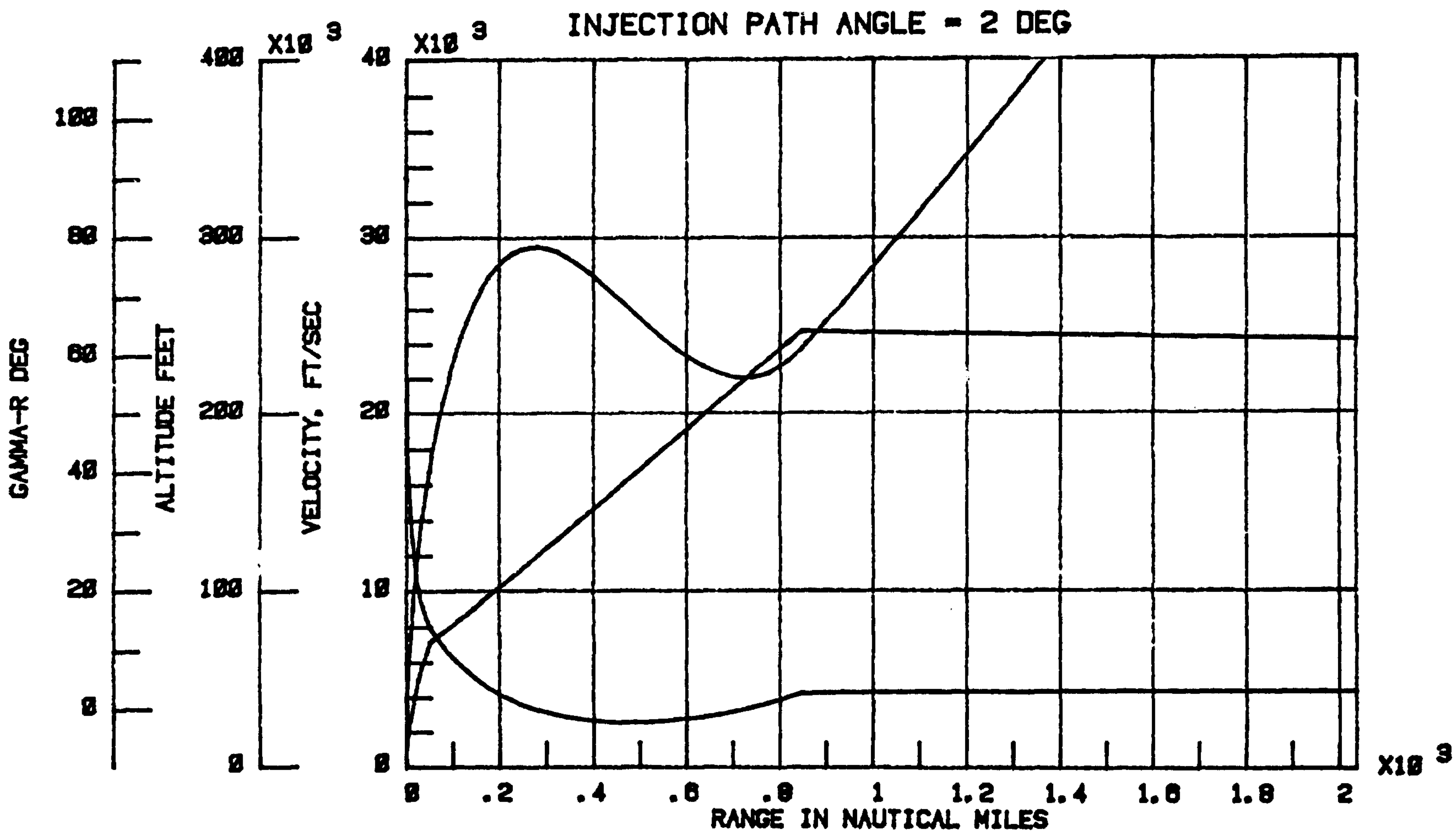


FIGURE 12 HLLV SUPPRESSED #4

(SAME AS #3 WITH LIFT & VAR DRAG ADDED)



Winj = 1.9028

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FIGURE 13 HLLV SUPPRESSED #4

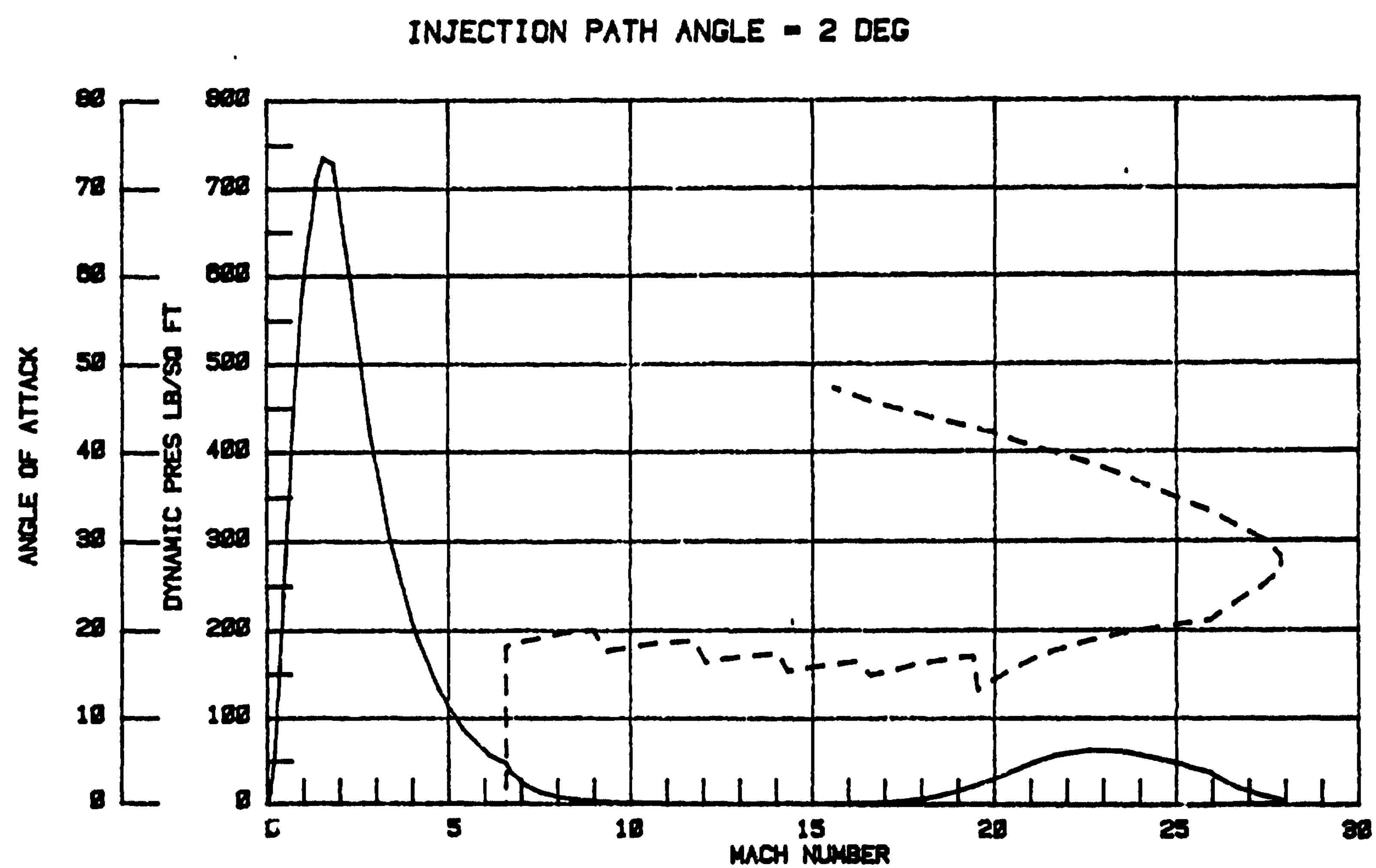

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FIGURE 14 HLLV SUPPRESSED #4

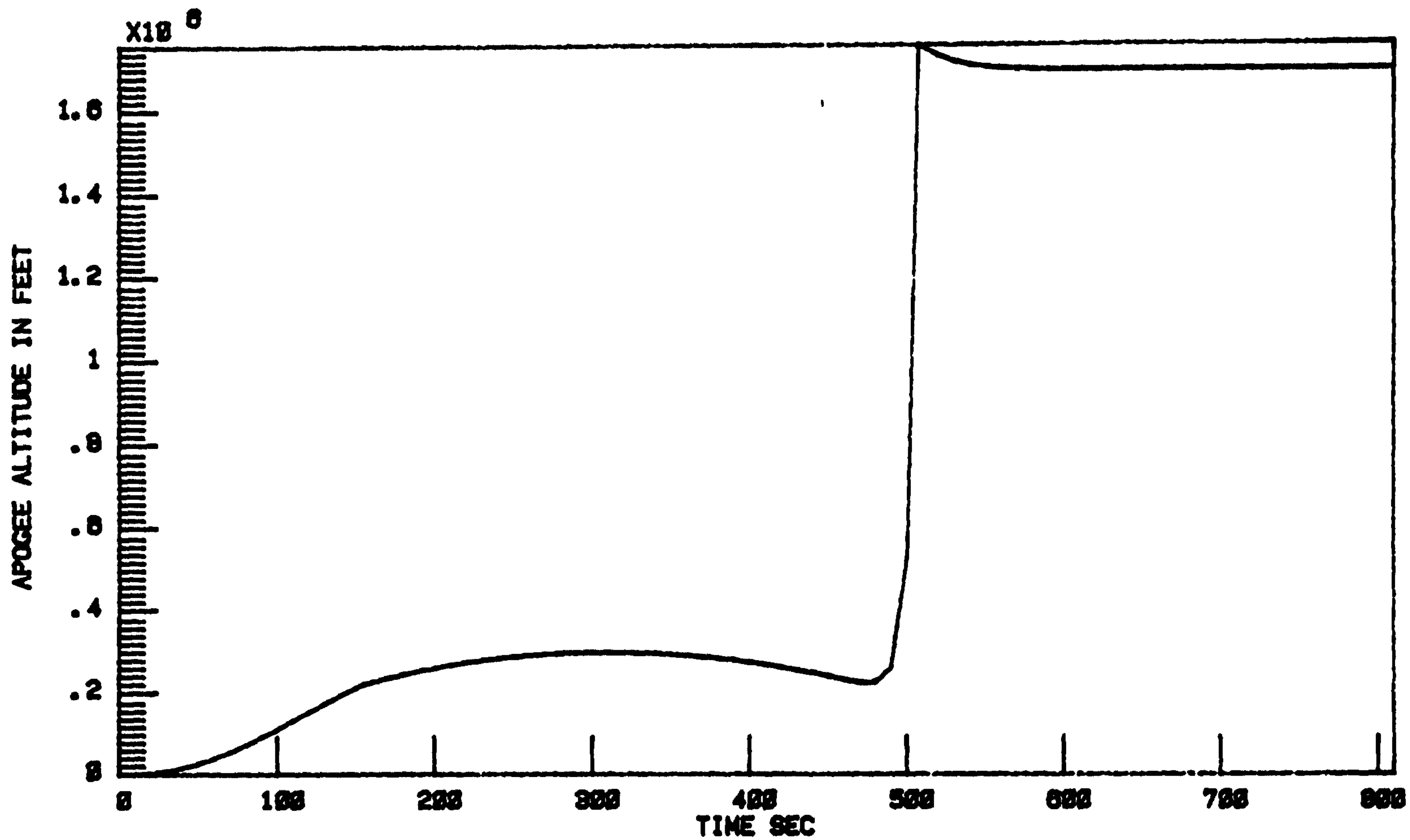
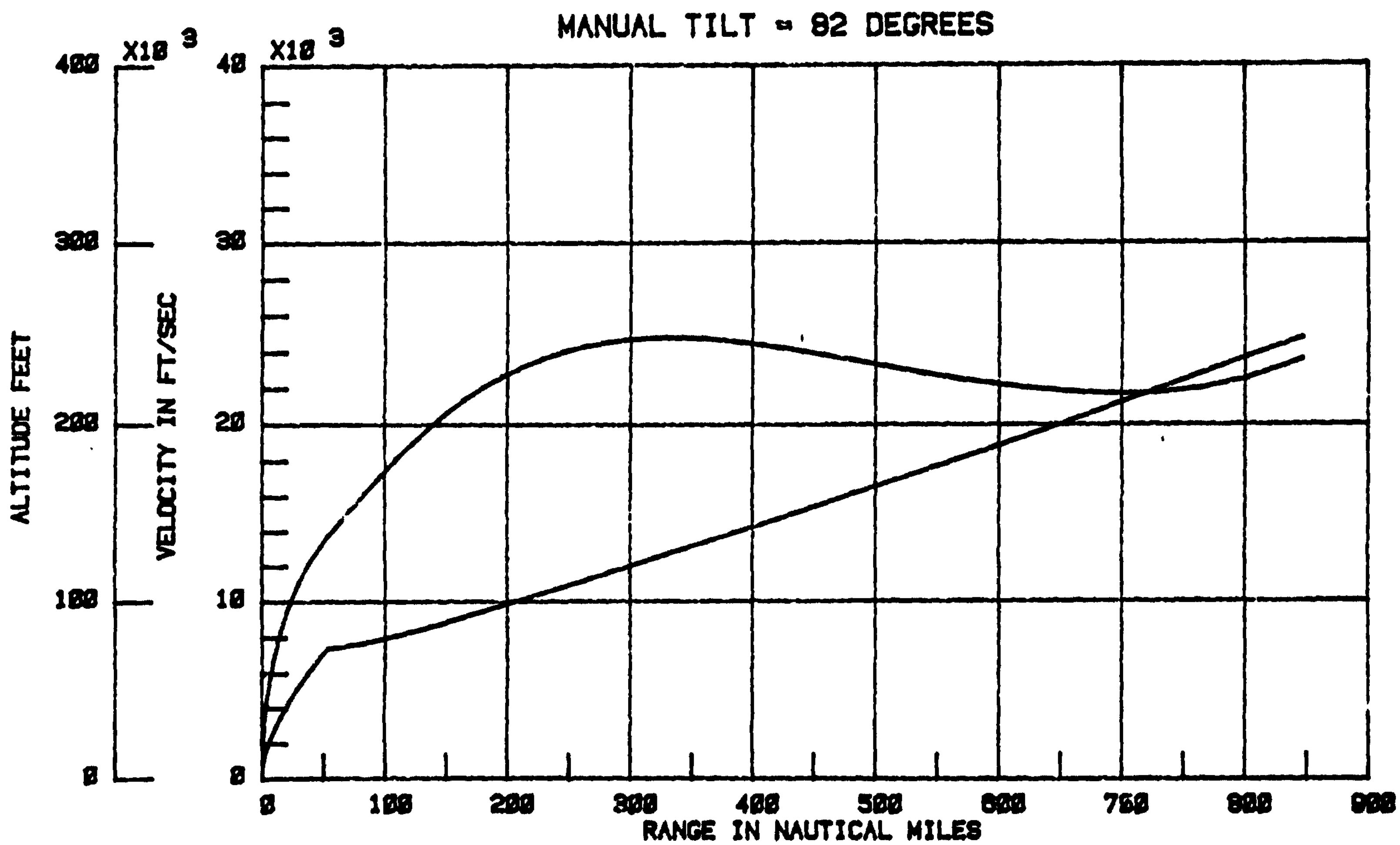


FIGURE 15 HLLV SUPPRESSED #6



D180-25461-4

FIGURE 16 HLLV SUPPRESSED #6

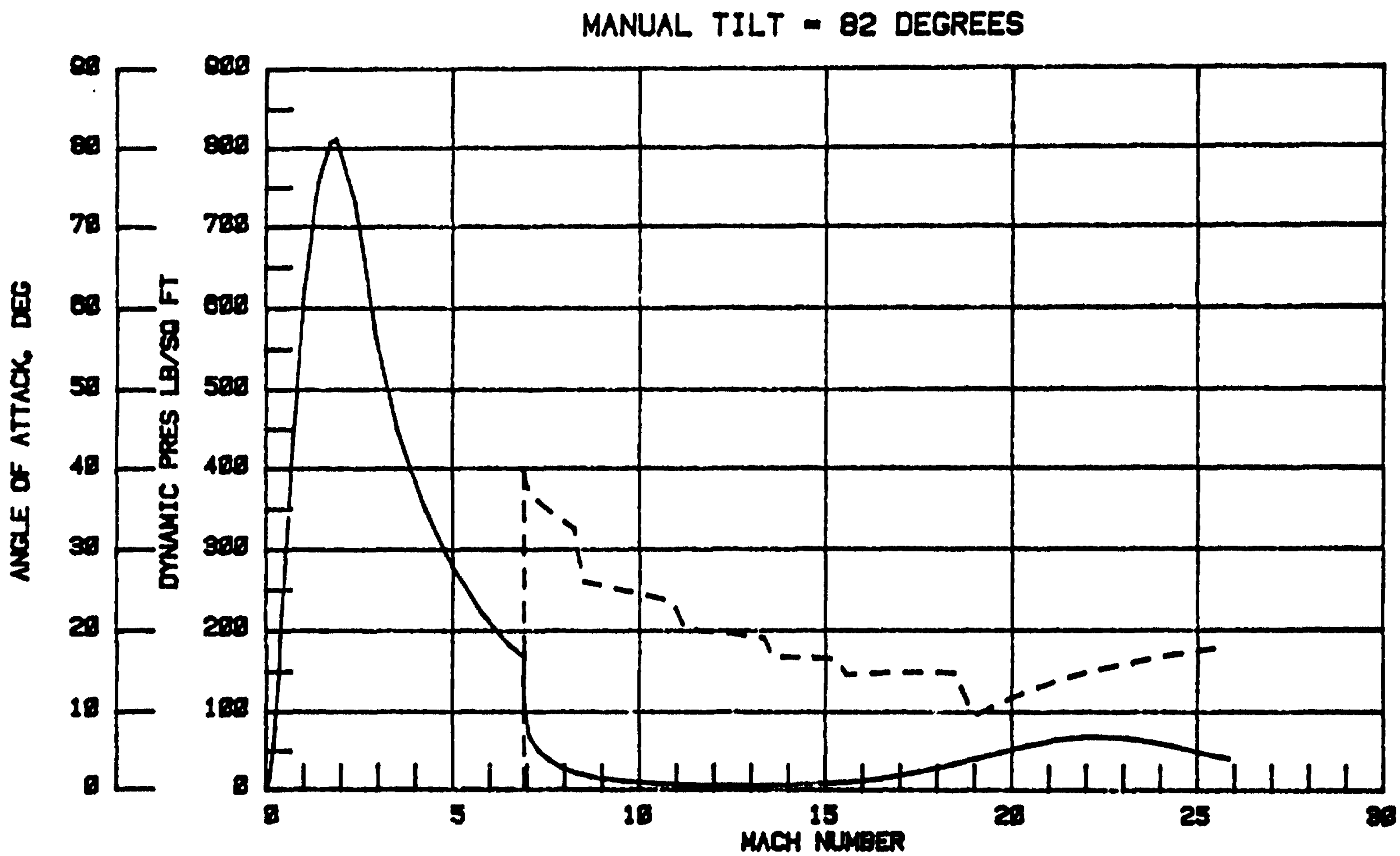


TABLE 1

LIFTOFF MASS: 10,975 Metric tons

TILT: 82^o

MAXQ: 38.8 kpa (811 psf)

STAGING:

V_{Rel} = 2236 m/s (7337 ft/sec)

H = 42 km (137,000 ft)

γ = 7.56 deg.

PEAK ALTITUDE: 75.47 km (247,672 ft)

INJECTION: 71.8 km (235,793 ft)

MAXQ AT HIGH HEATING 3.35 kpa (70 psf) (at Mach 22)

INJECTION PATH ANGLE - 2.56 Deg

INJECTED MASS = 840 tons (1.852×10^6 lb)

CIRCULARIZATION PROPELLANT = 30.2 tons (66,580 lb)

NET PAYLOAD: 379 tons (836,200 lb) (optimal (unconstrained) trajectory yields 420 tons)

FORWARD

This report presents the results of a five-man week effort to develop two conceptual designs of an Offshore Space Center facility and to establish preliminary cost estimates for each. This effort was performed by Brown & Root Development, Inc. for the Boeing Aerospace Company (Seattle, Washington) as a sub-contractor under contract N-A53036-9178 with the National Aeronautics and Space Administration, Johnson Space Center in Houston, Texas.

This preliminary investigation conducted in September, 1979 was restructed to two of several possible offshore design concepts. The results will provide guidance for future study and development of an optimal Offshore Space Center configuration and design.

OFFSHORE SPACE CENTER

FINAL REPORT

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OFFSHORE SPACE CENTER

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EXECUTIVE SUMMARY

Significant Results of the OSC Study

1. The OSC is feasible technically and would take approximately 6 years from conceptual design to completion.

2. The total installed cost estimates are $3,005,000 for the moored semi-submersible OSC and $3,917,000 for the stationary pile supported OSC. Runway cost for each is a significant cost driver.

3. The equitorial-based OSC concept has real benefits:
   - 20 percent more payload to ecliptic plane
   - 1 per cent more initial rotational speed of earth
   - Central location for transportation
   - Isolated from people, environmental effects
   - Independence of foreign control
   - Acceptable site(s) do exist
   - Mild climate with excellent weather and orbital windows

4. Additional work needs to be done on
   - Other concepts and combinations
   - Optimazation of OSC facilities and supports
   - Development of life cycle costs
   - Impact of the OSC on the NASA space program

1.0 INTRODUCTION

A study to develop concepts for an Offshore Space Center (OSC) facility for the National Aeronautics and Space Administration (NASA) was performed by Brown & Root Development, Inc. The OSC study included two conceptual designs of an offshore launch installation. Preliminary cost estimates were generated for each of the two designs considered.

The two concepts considered are a moored semisubmersible OSC and a stationary, pile supported OSC. Each facility included the necessary features of a space center complex such as a 15,000 foot long runway, three launch platforms, fuel and cargo areas, dockage, an airport, a control and operations center, and other support areas. A schematic of the proposed OSC facility is shown in Figure 1.1.

The facility was arranged to accommodate a two-stage winged launch vehicle of the type shown in Figure 1.2. Both launch and landing loads of each stage were considered during development of the support. The offshore environment and other operational requirements were analyzed to establish the feasibility of the conceptual design.

1.1 BACKGROUND

NASA has been involved for several years in the study of large solar power satellites (SPS) using solar arrays located in geosynchronous orbit. Such solar power collected in space can be beamed with microwaves to an earth based rectenna which can then supply electricity to the utilities' power grid. The construction of

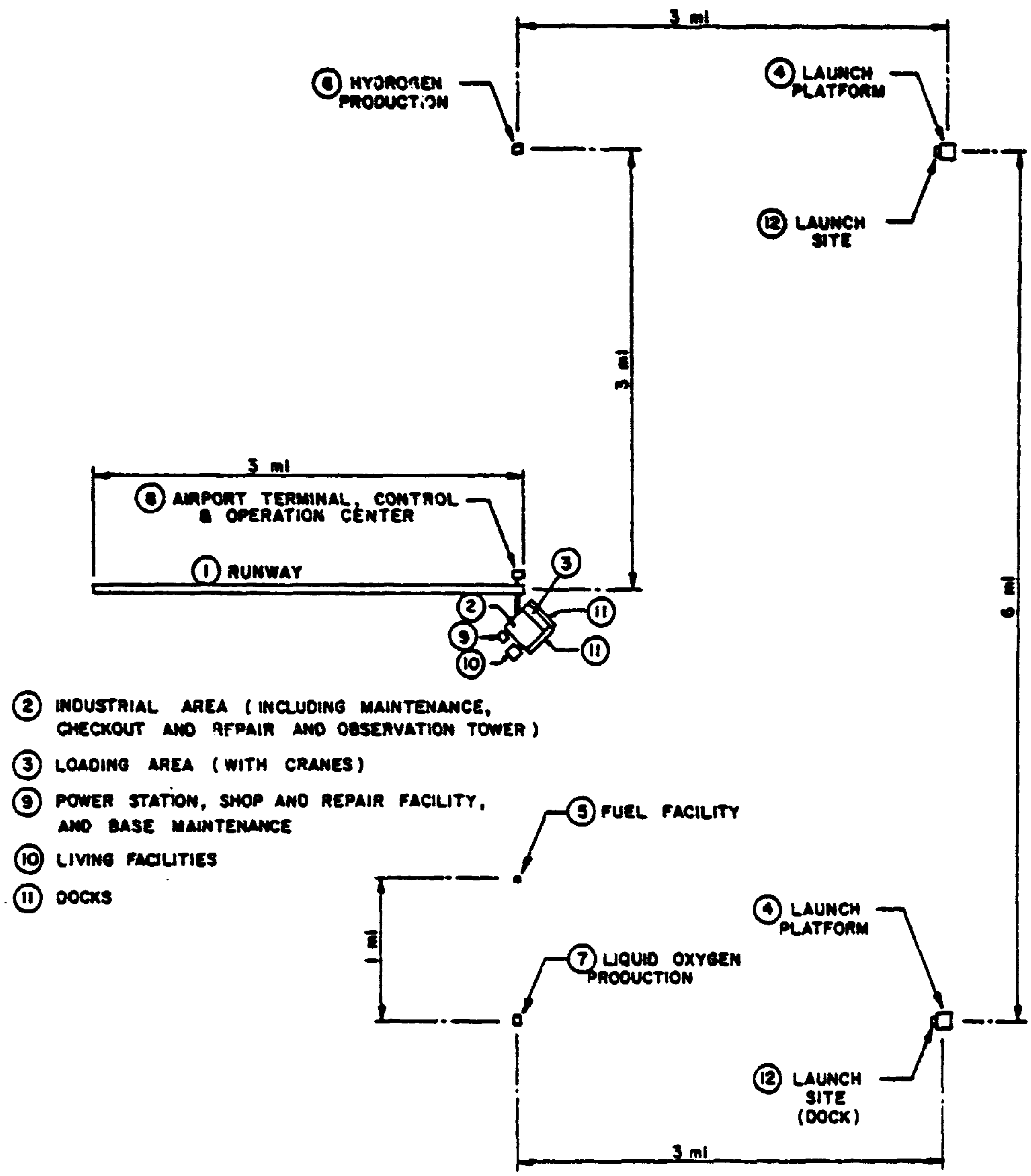

FIGURE 1.1 FACILITIES SCHEMATIC

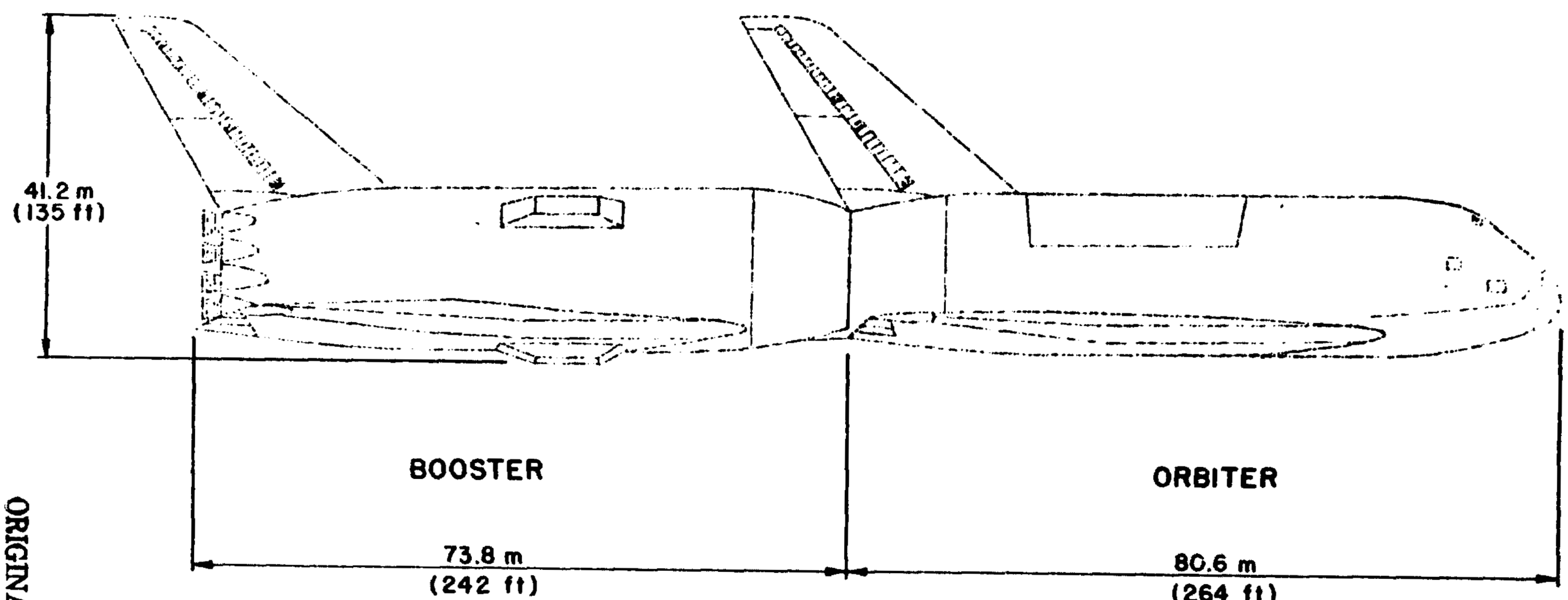

FIGURE 1.2 SPACE FREIGHTER-COMPLETELY REUSABLE

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these satellites using material from earth requires the transportation of large quantities of material to orbit. A fully reusable launch vehicle would be an economic necessity for such a scenario to carry the cargo for any project which is as massive as an SPS system.

Selection of the launch site affects the launch and orbit transfer costs considerably. For example, approximately a 20% improvement in payload to geosynchronous equatorial orbit (actually the ecliptic plane) can be achieved by moving the launch site from 30° latitude to near the equator. The near equatorial site offers the feature of a launch opportunity every 90 minutes, where the 30° latitude site allows only two launch opportunities per day. This operational flexibility of the equatorial launch site may significantly reduce the operations and the facilities costs.

Since the United States does not have total and direct control of any land in the equatorial region, an ocean installation outside any territorial waters is desirable. Such an installation may minimize political problems and will provide for easy access by using ocean transportation. Access by ship is very desirable since most of the items involved in a project such as SPS construction will be large and may be delivered from anywhere in the world.

Several other advantages inherent in an offshore launch facility of this type are:

- Reduced air and noise pollution to a populace in the denser air found offshore
- Greater winglift for the SPS launch vehicle stages and space center supply planes
- Better control on landing or reentry in such air by planes or launch vehicle stages
- Increased aircraft engine efficiencies and less engine effort are possible.

Chemical pollution of the air is a greater problem on land than offshore because of the proximity of the population. A key concern for persons in the flight path of the space shuttle or a similar vehicle is safety. Objections have been expressed with increasing frequency and fervor by the public on Florida's East Coast about the trajectory of some of the planned launches. An ocean site will minimize such public resistance and possible conflicts with air flight patterns. Interference with airports will be avoided and the reduction of crash danger is evident with the offshore concept.

The OSC structure at the specified area in this study would not degradate existing fishing grounds, shipping lanes, or recreational areas. In fact, such structures typically act as an artifical reef, attracting and supporting aquatic life. Fishing opportunities may be enhanced and both extensive and intensive mariculture are

possible additional benefits that may be derived from the offshore complex. Natural water currents and tides would not be inhibited nor would the ocean environment be significantly threatended from such activity.

The facility would be modular in construction and an ocean siting would permit unlimited expansion of additional facilities as required. Construction of additional modules need not interfere with flight operations. Upon completion such modules could be towed to the complex and connected.

1.2 OBJECTIVES

The OSC Study was undertaken to establish a credible data base for costs of an offshore complex. An objective was to define two conceptual structural designs for installation in a location near the equator in Pacific Ocean waters 600 feet deep. This depth is assumed to be typical for the Paramount Seamount location. The analysis includes an estimate of the weight and cost for the OSC facilities. The types of facility concepts considered are:

1. Semi-submersible moored platform
2. Stationary platform with pilings or other structure supported by the sea bed

1.3 SCOPE

These conceptual designs are of necessity limited in scope. Both of the proposed conceptual designs were developed for the 600 foot water depth. Design variations for other depths are not within the scope of this effort. Greater depths would have a significant escalating effect on costs (particularly the pile-supported concept) and would necessitate alternation of the designs. Costs increase rapidly (non-linearly) with depth of water.

The proposed conceptual designs are used only for the estimation of cost data. Costs are estimated for fabrication, construction and installation of both OSC concepts.

The facility uses marine construction technology, materials, manufacturing techniques, and installation methods which are currently available or expected to be available for the projected 1985 construction initiation. Additional technical development in some areas could beneficially impact the design and associated costs.

2.0 DESIGN REQUIREMENTS

For this study, the design requirements encompass the structural design concepts, specific facility features, launch site environmental parameters, and operational loads and requirements. Each OSC concept was developed to the conceptual design stage with respect to these established guidelines. Development of a design was conducted only to a point, whereby preliminary cost estimates could be made.

The launch center arrangement was configured to handle two stage heavy lift launch vehicles (HLLV) which take off vertically from a launch pad. The first stage (upon expenditure of its propellant, at about 200 miles down range) returns and lands on the runway much as an aircraft would.

The second stage continues into orbit. It returns from orbit and lands after the payload is delivered. Launch rates currently being considered are two flights per day, 5 days a week, using a launch vehicle which delivers approximately 1,000,000 pounds of payload to low earth orbit per flight.

The OSC must be able to handle the expected rocket, airplane, and ship traffic. Primary considerations in the design of any offshore structure are (1) depth of water, (2) weather conditions, (3) protection of the environment and ecology, (4) wave effects, and (5) economics. For floating structures, the design must assure floatation, anchorage and the connection of the floating modules. Vessel stability and the motion responses in the waves are key design concerns for the moored OSC concept. While runways need not be perfectly flat and level, variations in the longitudinal grade will increase the required landing distances.

Another design consideration for any offshore concept is maintenance. Any final design must reflect an effort to minimize the cost of maintenance. The design should reflect the state of development of currently possible installation methods.

2.1 LAUNCH SITE ENVIRONMENT

The OSC should be fully operational within expected operating environments and must survive expected extreme environments. Possible environmental design criteria considered during a preliminary design study may include currents, waves, winds, tides, storms (cyclones, typhoons, and hurricanes), tsunamis, and possible earthquake disturbances. Loads caused by some of these natural occurances are especially critical for the anchorage system of the floating OSC facility while others may be more critical to the piles supporting the stationary design.

A detailed design of the OSC requires the knowledge of tidal ranges, currents, waves, and swells (including directions, and wave lengths, heights, and frequencies), soil characteristics of the bottom, water depth, and meteorological data covering winds and temperature.

Two near-equatorial sites in the Pacific Ocean have been reviewed by the Johnson Space Center, NASA-Houston and appear to offer possible advantages over launch from the Kennedy Space Center in Florida. These sites (shown in Figure 2.1) are: Paramount Seamount at 3^{o}N, 91^{o}W and Villalobos Seamount at 7^{o}N, 111^{o}W. The Paramount Seamount minimum water depth is about 570 feet and Villalobos is about 2640 feet below the surface of the Pacific. The bottom in both of these locations is considered by geologists to be solid rock, with a few feet of sediment covering the surface.

The weather in this area has been determined by NOAA to be very mild, with daily temperature maximums of 88°F and minimums of 66°F. Light winds are typical of the area. Wave heights are typically below 4 feet for 80% or more of the time and wave heights higher than 12 feet have never been observed in these areas. Sea swells from distant antarctic storms could be significant, however, since the typically large structures will have natural periods nearer those of swells than those of waves.

Tidal waves are typically of very low amplitude due to the general water depth in the area and very long wave length. Tidal waves increase in height and have a shortened wave length as they run up into shallower water. The current in the area is typically low at about 1/2 mph, but occasionally, with the shift of the Humboldt current, can be as large as 1 mph for extended periods.

2.2 STRUCTURAL DESIGN CONCEPTS

Conceptual designs were developed for each type of OSC. The basic arrangements are shown in Figure 2.2. A pile supported complex with some modules which are floating and a semi-submersible structure which is floating and moored have both been considered.

The bottom of steel (elevation of the lowest horizontal steel members) for the runways and taxiways for the pile supported concept was specified to be at an elevation of ten (10) feet above the maximum wave height for 100 year storm condition with surge and tide. The runway to support the landing of the HLLV stages is sized to be 300 feet wide and 15,000 feet long and will, of necessity, contain extra structural support in the area of touchdown.

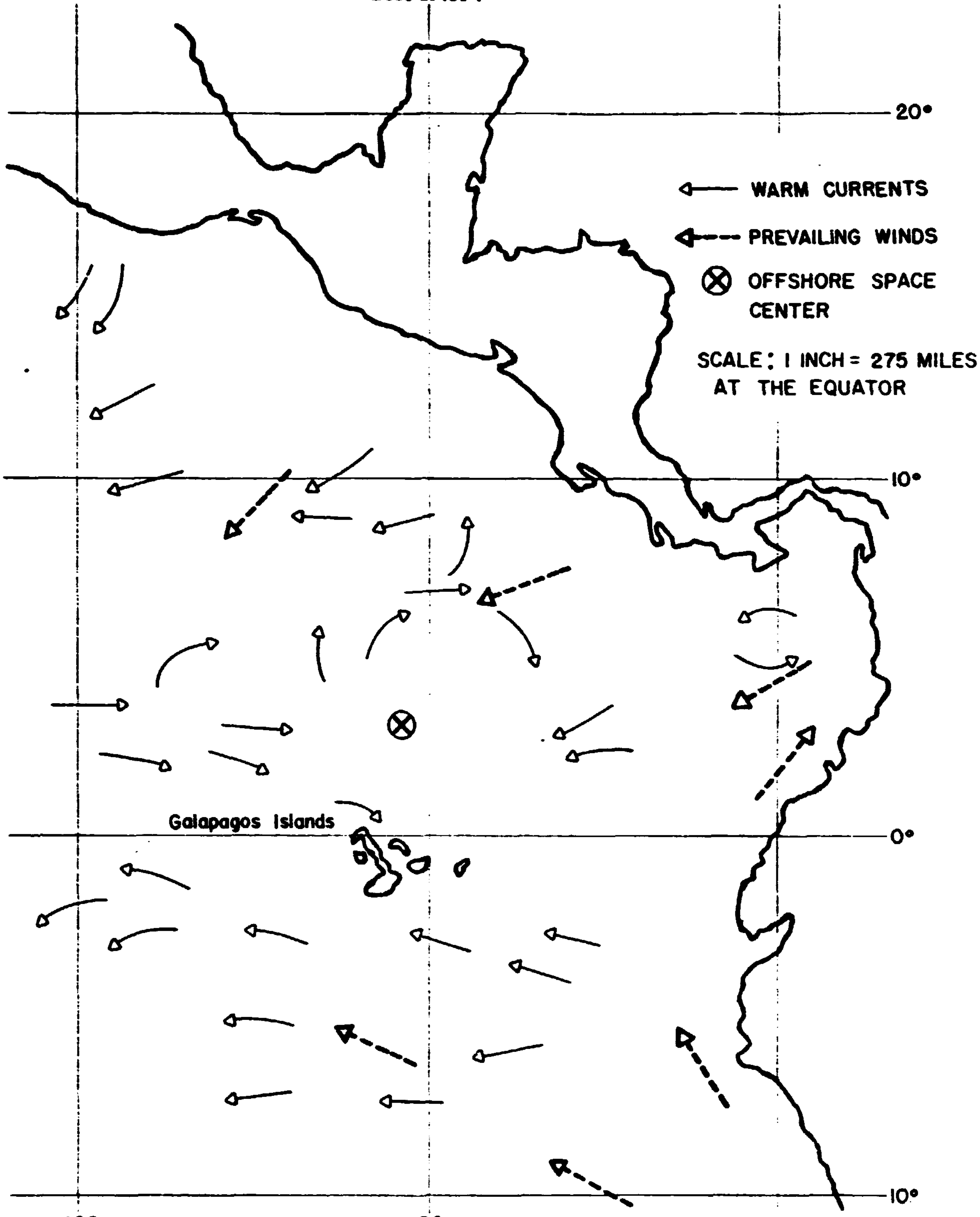

FIGURE 2.1 LAUNCH SITE

The launch platforms are mobile and able to carry the unfueled vehicle with up to a one-million pound payload to the launch site, erect the vehicle, fuel it, retract the erection system, and support launch. Maximum landing loads impacting the runway and launch platform loads are presented in Section 2.4. Specific requirements of support facilities are included in the following section on facility features.

2.3 FACILITY FEATURES

This study involves only the conceptual design of the OSC structural support, although consideration is given to the facility features which will be supported.

The design of the features required at such an offshore space complex are based upon several factors. Consideration of the various factors allows the compilation of required design features. A full list of the major componnents of the OSC and dimensions of each are presented in Table 2.1.

The facility is layed out to minimize possible conflict with aircraft, the SPS launch vehicle, and the fuel and personnel facilities. Runway approaches and takeoffs are directed away from potential dangerous areas such as the fuel storage area.

A runway, a taxiway. and a parking apron are required for the two stages of the SPS launch vehicle and support aircraft. All other airport requirements are inherent in this design such as:

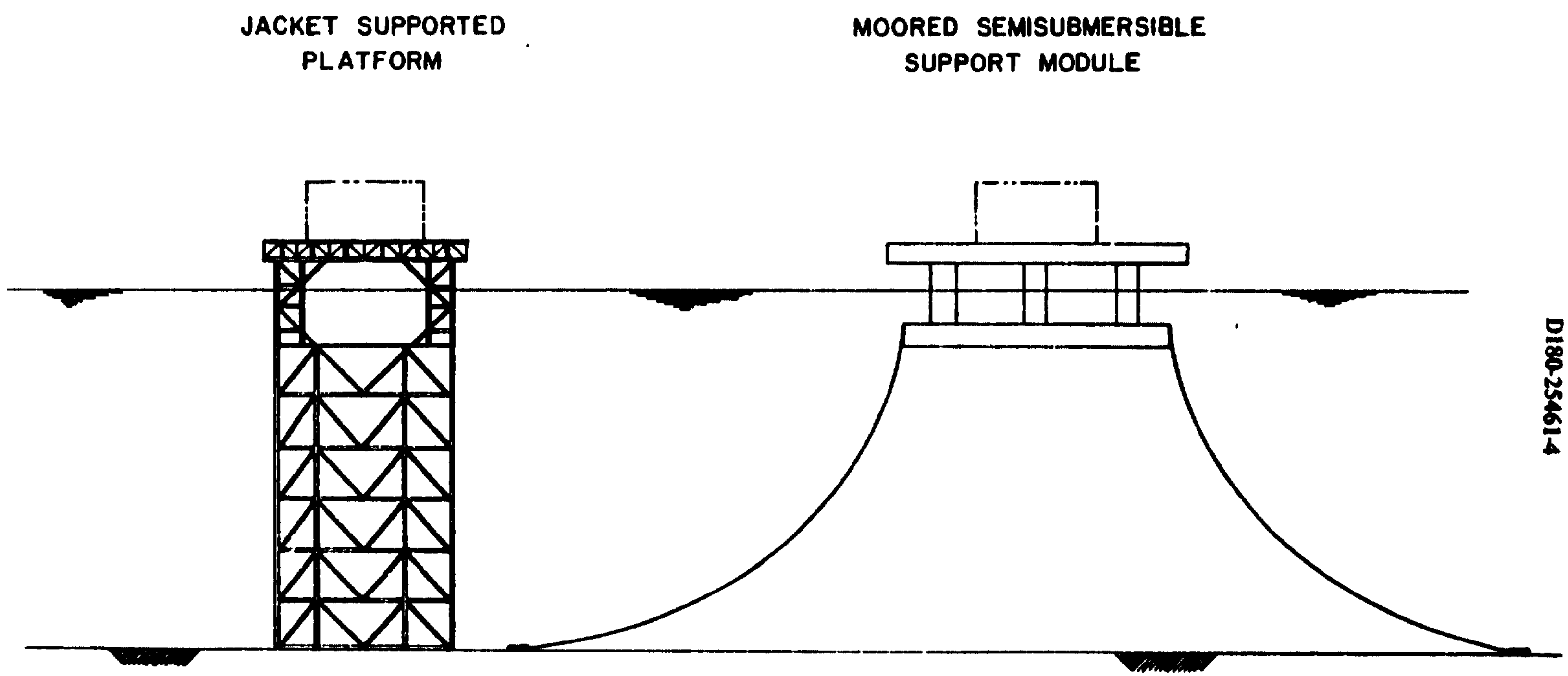

FIGURE 2.2 SUPPORT CONCEPTS

(1) navigational aids, (2) lighting, (3) communications, and (4) air traffic control facilities. A computer operations center is included in the air traffic and launch control module.

Cargo and mail facilities are provided at the airport. Container yards, roll-on/roll-off areas, cargo handling and lighter aboard ship systems are included. A nearby loading area with two 1.7 million pound capacity (of 135 feet hook height) cranes handles the air and sea cargo shipments.

A seaport allows dockage of the ships which carry launch payloads, supplies, and other materials. Base maintenance and servicing facilities and a repair facility including a machine shop. an electrical shop, and a paint shop are needed for the OSC. The repair, maintenance, and checkout facilities are incorporated into an industrial area module.

Dockage at a specific site is included for the launch platforms. Propellant supply connections are available at each dock. The hydrogen production and liquid oxygen production areas will each support chemical processing plants. A fuel facility with dockage and transfer connections for a large methane or LNG tanker is included in the complex.

Emergency facilities such as a fire station with fire control units are included in each facility. The hotel area houses the hospital

and equipment needed for platform and sea crashes and other potential accidents. A base security station is included with appropriate air and sea defensive equipment to prevent sabotage. A nearby power station provides the needed base power for operation and utilities.

A 'hotel' capable of accommodating 10,000 persons will provide living facilities, food preparation and cafeteria, sanitary facilities, and recreation on the complex. Stores and a fresh water supply are included in this area. A waste disposal and sewage treatment plant is required nearby.

TABLE 2.1 - OSC FEATURES

	AREA	QUANTITY	APPROXIMATE SURFACE AREA
1.	Runway	1	300' x 15,000'
2.	Industrial Area (including Maintenance, Checkout and Repair and Observation Tower)	1	1100' x 900'(x 150' high)
3.	Loading Area (with cranes)	1	300' x 1100'
4.	Launch Platform	2 + Spare	500' x 500'
5.	Fuel Facility	1 + Spare	100' x 100'
6.	Hydrogen Production	1 + Spare	200' x 200'
7.	Liquid Oxygen Production	1 + Spare	200' x 200'
8.	Airport Terminal, Control and Operation Center	1	200' x 300'(x 7 stories)
9.	Power Station, Shop and Repair Facility, and Base Maintenance	1	200' x 300'(x 3 stories)
10.	Living Facilities	1	400' x 400'(x 12 stories)
11.	Docks	2	200' x 1200'
12.	Launch Site	2	Dock (200' x 300')
13.	Tug Tanker/Barge (For Cryogenic Work)	4	---

2.4 OPERATIONAL REQUIREMENTS

Certain operational requirements have been imposed on the OSC design. These requirements determine the support structure design of each of the areas specified in the previous section. The surface area required for each of the OSC features is presented in Table 2.1.

The OSC alignment reflects the desirablity of aligning the runway in the direction of the prevailing winds and currents. Likewise, it is customary to have the prevailing winds blowing a ship off of a dock and the facility has the dockage aligned accordingly whenever possible. Both of these factors determine, to an extent, the general orientation of the OSC shown in Figure 1.1.

Provisions will be made during final design of the runway for the containment of aircraft and SPS launch vehicle stages to prevent them from going overboard. The strength of runway surface and platform substructure for various features of the marine facility are determined from expected air vehicle loadings. The maximum landing load (estimated by NASA at 2.5 million pounds) will be for the booster stage of the launch vehicle which weighs about three times as much as a Boeing 747. Both the first and second stages have a touchdown velocity of approximately 150 knots.

The launch platform supports the fully fueled launch vehicle and a one million pound pay load. This is a floating platform for both OSC structural concepts and serves in an additional capacity as the

launch vehicle transport. The chemical processing plants (in both the hydrogen production and the liquid oxygen production areas) each weigh ten million and the power plant facility weighs ten million pounds.

3.0 STUDY METHODOLOGY

A study methodology is required to allow rational program decisions regarding order of magnitude cost estimation of conceptual designs within the program requirements. For both OSC concepts, the costs are estimated for the assumed conceptual design development, the construction, and the deployment of the OSC. The estimated costs (in 1979 dollars) are based on background and historical data coupled with assumptions about the detail of required conceptual design development.

If the SPS program proceeds, a signficant fraction of the United States productive capacity will be involved. It is desirable that the potential supplies of all items required be readily available to foster a competitive environment and minimum cost for system acquisition. With this in mind, the concepts are constructable in modular form with typical marine construction techniques. Foreign facilities may be considered, using the OSC site for final assembly.

Both OSC concepts will involve some development of existing offshore technology in order to realize a project of this magnitude. The conceptual designs are within the state-of-the-art technologically and a capability exists to establish such a complex at a site near

the equator. A knowledge of developments in both marine and airport projects is important to the advancement of an OSC design beyond the conceptual phase.

3.1 CONCEPTUAL DESIGN APPROACH

In the conceptual phase of the OSC design, numerous trade-off studies will be required to arrive at the most promising solutions for further development of a design suitable for cost estimations. In future studies, resources should be focused on specific design issues and engineering details to establish a well defined OSC. The scope of this work does limit the design effort that this program can expend to ensure an effective means of estimating costs.

Two OSC concepts have been suggested by NASA and a few conceptual design approaches have received considerable attention. Establishing general guidelines, this study proceeded to identify baseline designs for both of the suggested concepts. Proposed subsystems were evaluated to determine if they meet OSC system requirements for technical feasibility, availability, and deployment schedule.

The question of concept definition is broader than may first come to mind. In addition to design configuration, included are the methods of fabrication, construction, and installation. The design configurations have been sized for the operating loads. OSC subsystems interact with the configuration in terms of loads induced on each other and the interfaces required. Thus, concept synthesis requires consideration of all phases of the design process.

The design approach assumes that a system of modular structures using standardization of construction, material, and installation techniques is the most cost effective method of producing the OSC facility. Site selection for both types of offshore structures and utilization of appropriate transportation facilities are assumed optimal in the design approach.

The OSC configuration is based on wind, wave, docking, and landing loads. Base operations and buffer zone areas are important considerations in the layout as well as the logistics of transportation and traffic. An additional design input into the OSC configuration is the technology of offshore installation methods.

A criteria was established to develop a conceptual design for a piled jacket concept and the moored semi-submersible concept. OSC features were arranged to get optimum use from the supports in each case.

Stationary platforms were established for all features and the number required for each were estimated from the predicted weight and surface area requirements. The Launch Platform and Tug Tanker Barges were considered semi-submersibles for both OSC concepts. Typical jacket structures normally used in 600 feet of water were assumed for the piled jacket concept.

The semi-submersible configuration was developed from the design and environmental parameters assumed in Section 2.0. Conceptual column design, pontoons, and deck design for the runway and launch platform were established to develop a rough estimate of costs. The data for these platforms was then used to extrapolate costs for the other semi-submersible modules based on area and loading.

Relative motions of adjacent structures and between structures and the various vehicles required in the operation of the OSC must be considered for both structural loading purposes and for operational envelopes and analyses.

3.2 COST DETERMINATION

To make an equatorial launch site attractive, a cost trade off between the OSC facility construction cost, and the transportation of fuel, manpower and payloads to the equator versus the improvement in payload and operation expenses must be made. To determine facility costs, a rough estimating methodology had to be developed to determine the order of magnitude costs.

The costs of the OSC facility features have been estimated based on weight and area predictions. Experience with similar structures established a background upon which the cost estimates were made. Only the costs of the facility support structure itself (and the

mooring system for the floating concept) is considered; not those for the equipment, tools, etc. involved in the launch operations. For example the power station estimate does not include the cost of the power plant, only the cost of the area on which to install the power generating equipment with adequate support to permit it to function.

NASA will estimate the costs of the necessary equipment and other installations. The OSC cost estimate does include the cranes in the industrial area and an estimate of costs for on-site cryogenic fluid delivery between the propellant facilities and the launch sites. This delivery system would consist of a number of suitable specialty barges and shuttle tugs. Use of this type of fuel transportation system would be more reliable and cost effective (considering life cycle costs) than use of present subsea cryogenic pipeline technology.

The OSC cost estimates which apply to the facility features are presented in Section 4.2. The extrapolated costs for the semi-submersible platforms (from the runway and launch platform calculations) were first directly ratioed to the area required and then increased by a weight factor for heavily loaded platforms. This factor of 1.8 was calculated by dividing the heavy launch platform cost by its estimate.

Estimates of cost are based on current experience in the fabrication and installation of offshore structures. The costs are expressed in 1979 dollars without adjustments for inflation between now and the completion of construction which is estimated to take six years from the conceptual design phase.

4.0 RESULTS

The effort expended to develop two conceptual OSC designs and to estimate their order of magnitude costs, established a data base from which to draw information for further, more detailed studies.

Both concepts are feasible and relatively inexpensive considering the potential savings involved from the establishment of an offshore-based launch complex near the equator. The concept costs range from 3.005 billion dollars to 3.917 billion dollars with the semi-submerisble support structure being the less expensive. However, discretion should be used in comparison of the two figures. Neither concept was optimized. In reality, a blend of the types of supports would probably be cost effective. The OSC facility cost could thus be reduced through further ocean systems engineering studies.

The final conceptual design parameters are presented in Section 4.1 and results of the cost analysis in Section 4.2.

4.1 CONCEPT BASELINE DESIGN

Two conceptual designs were developed for the OSC and each is similar in layout of the features. Both baseline designs utilized modular construction techniques which were feasible. Each conceptual design was developed only to a point where an initial estimation of costs could be achieved.

The runway, floatation system, and mooring systems for the semi-submersible moored platform concept is shown in Figure 4.1. The runway in particular must be designed to account for the variable water elevation along its length and the moving load of the landing vehicles. Consideration must also be given to the lateral deflection of the structure along its length. If the structure cannot be designed in a preliminary engineering phase to accept the moments developed from deflections, then hinges must be incorporated in the structure to relieve this loading. Other alternatives which might be investigated in further studies and which may impact costs include active mooring winches or dynamic positioning equipment to relieve lateral deflections.

The airport, industrial, and other facilities in this design concept, shown in Figure 4.2 have been arranged for efficient and cost effective support. Since additional facility surface area on the ocean translates into higher costs, the OSC was arranged to minimize the supported areas. The launch platform concept will be a semi-submersible for both OSC concepts and is shown in Figure 4.3.

The runway for the stationary OSC platform with piling support is shown in Figure 4.4. The pile supported OSC will require a higher elevation than the semi-submersible due to varying tidal heights and swells. The runway must not be inundated during high seas and a level runway must be maintained for safe landing. The runway surface is designed to be 40 feet above the mean water level and the platform supports are placed on 300 feet centers.

4.2 COST ANALYSIS

Only preliminary (order of magnitude) cost estimates were performed for each of the two OSC concepts. Costs were estimated for each facility based on weight projections and area requirements for them. These cost estimates, based on U.S. manufacturing, are presented in Tables 4.1 and 4.2, respectively, for the moored OSC design and for the stationary, pile-supported concept.

The OSC facility with semi-submersible support structures was estimated to cost $3,005,000 (including the mooring). Major cost drivers were supports for the runway, industrial area, living facilities, and launch platforms. Runway estimates were based on a 15,000 foot length, and costs are scaleable for it on the basis of length. Need for such a long runway is questionable. At $95,500 per linear foot of 300 foot-wide runway, the costs could be reduced significantly through shortening its length.

Since the launch platform is a semi-submersible for both facilities, its cost estimate is identical for each concept. The semi-submersible was estimated at 143.2 million dollars each and two plus a spare are required. Cost estimates for the living facilities and industrial area were 203.7 million dollars and 315.1 million dollars, respectively.

The stationary, pile-supported OSC was estimated to cost $3,917,000 with cost drivers being the runway ($2 billion), the launch platforms ($429 million), the industrial area ($400 million) and the docks ($320 million). The cost per foot for the jacket-mounted runway was estimated to be $133,300. Again, a significant cost reduction could be achieved through optimization of the runway's length. However, a significant comparision can be made on the runway cost per foot for each concept. The jacket mounted cost can be more competative with the semi-submersible only through reduced water depth.

TABLE 4.1 MOORED SEMI SUBMERSIBLE OSC
COST ESTIMATE

NO.	FEATURE	COST ESTIMATE	WEIGHT FACTOR	QUANTITY	FACILITY COST (M$) FINAL COST (EA)	TOTAL
1.	Runway	1432.4	-	1	$1432.4	$1432.4
2.	Industrial Area (including Maintenance, Checkout, and Repair)	315.1	-	1	315.1	315.1
3.	Loading Area (with cranes)	105.0	-	1	105.0	105.0
4.	Launch Platform	143.2	1.8	3	143.2	429.6
5.	Fuel Facility	3.2	-	2	3.2	6.4
6.	Hydrogen Production	12.7	1.8	2	22.9	45.8
7.	Liquid Oxygen Production	12.7	1.8	2	22.9	45.8
8.	Airport Terminal, Control and Operation Center	50.9	-	1	50.9	50.9
9.	Power Station, Shop and Repair Facility, and Base Maintenance	28.6	1.8	1	51.5	51.5
10.	Living Facilities	203.7	-	1	203.7	203.7
11.	Docks	76.4	-	2	76.4	152.8
12.	Launch Site	19.1	-	2	19.1	38.2
13.	Tug Tanker/Barge	32.0	-	4	32.0	128.0
	TOTAL Semi-submersible Supported OSC (including mooring)					$3,005.

TABLE 4.2 STATIONARY PILE SUPPORTED OSC
COST ESTIMATE

	AREA	NUMBER PER FEATURE QUANTITY	JACKETS	BRIDGES	FACILITY COST (M$) FABRICATION	INSTALLATION	TOTAL
1.	Runway	1	40	40	$1400	$ 600	$2000
2.	Industrial Area (including Maintenance, Checkout, and Repair)	1	8	1	280	120	400
3.	Loading Area (with cranes)	1	2	0	70	30	100
4.	Launch Platform*	3	0	0	400	29	429
5.	Fuel Facility	2	1	0	70	30	100
6.	Hydrogen Production	2	1	0	60	20	80
7.	Liquid Oxygen Production	2	1	0	60	20	80
8.	Airport Terminal, Control and Operation Center	1	1	1	35	15	50
9.	Power Station, Shop and Repair Facility, and Base Maintenance	1	1	0	45	15	60
10.	Living Facilities	1	1	1	55	15	70
11.	Docks	2	3	2	220	100	320
12.	Launch Site	2	1	0	70	30	100
13.	Tug Tanker/Barge	4	0	0	108	20	128
	TOTAL Stationary Pile Supported OSC				$2,873	$1,044	$3,917

*Semi-Submersible

4.3 SUMMARY

This design study has been performed to develop a conceptual Offshore Space Center facility for NASA. Preliminary estimates of costs (in 1979 dollars) were generated for each of two concepts for installation in 600 feet of water with construction commencing in 1985.

The conceptual design considered two base-line designs: a floating, moored, semi-submersible OSC, and a fixed, pile-supported OSC. Each of these feasible concepts was analyzed for costs of fabrication, construction, and installation using current state-of-the-act techniques. An artist's rendering of the proposed OSC configuration is shown in Figure 4.5.

From the preliminary look at the two baseline design concepts and their associated cost estimates of fabrication, construction, and installation, it should be apparent that a mix of the two concepts (considered here) would be desirable. Overall costs of the proposed OSC facility is believed to be quite reasonable and attractive considering the advantages of such a project.

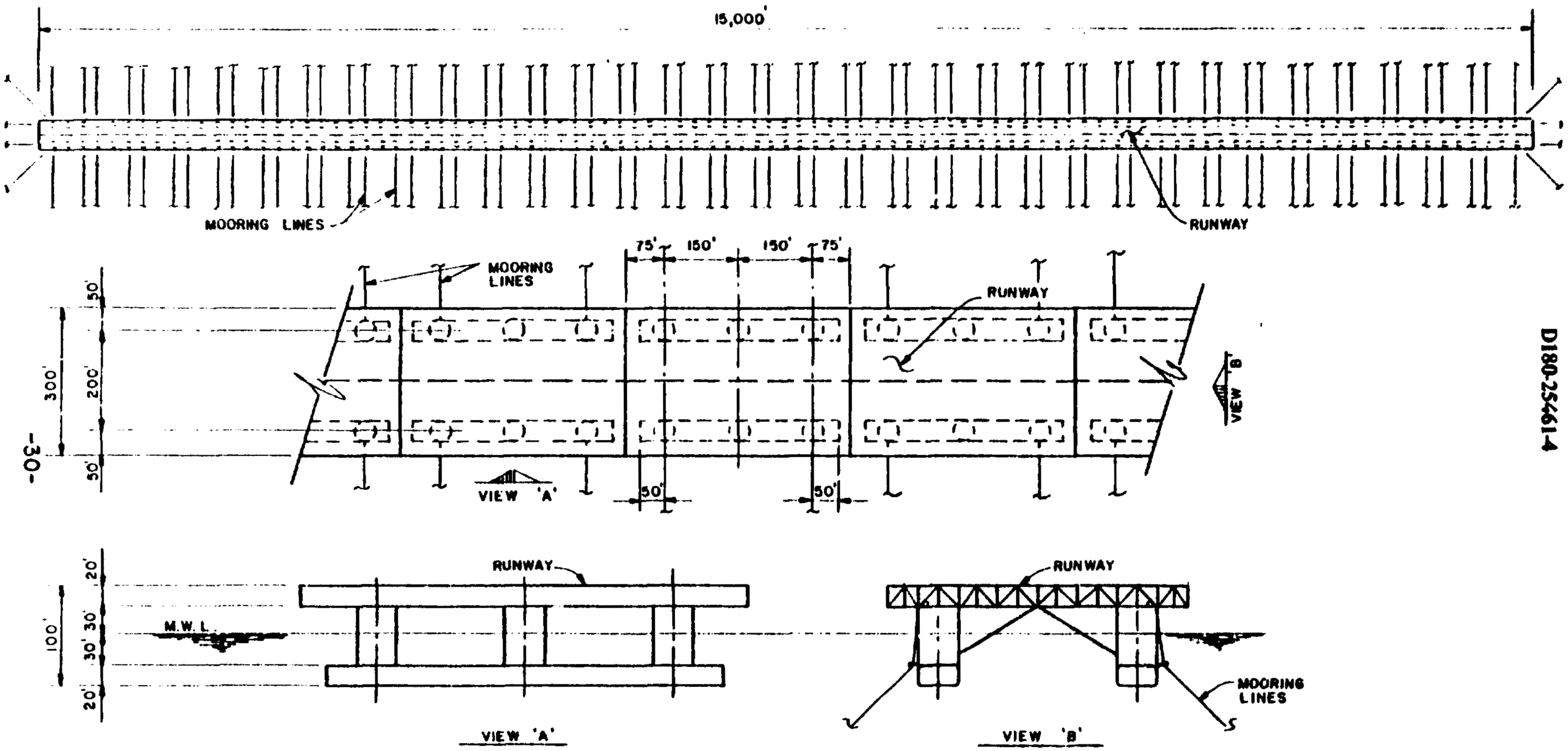

FIGURE 4.1 RUNWAY, FLOTATION, MOORING-SEMISUBMERSIBLE CONCEPT

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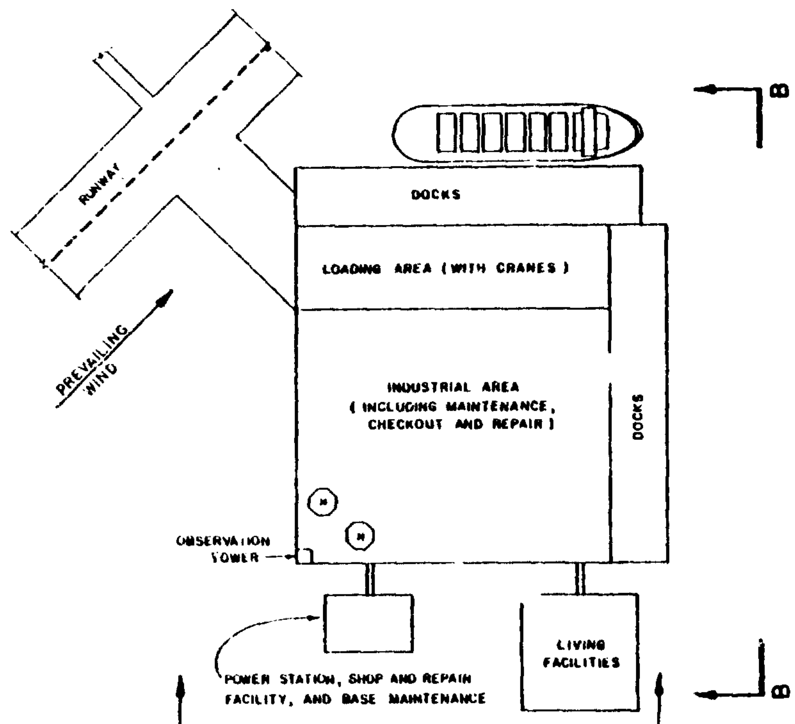

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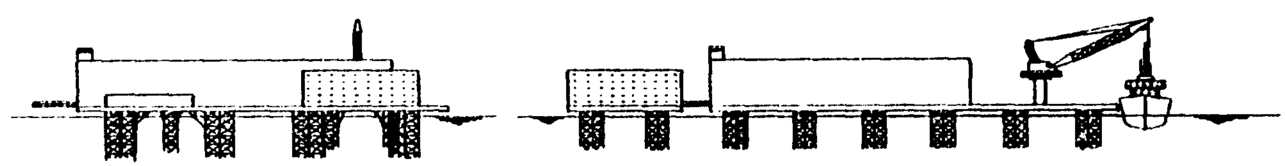
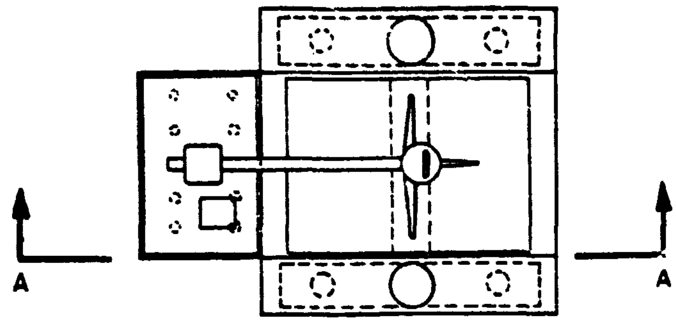


VIEW A-A

VIEW B-B

FIGURE 4.2 INDUSTRIAL COMPLEX, POWER, AND LIVING FACILITIES



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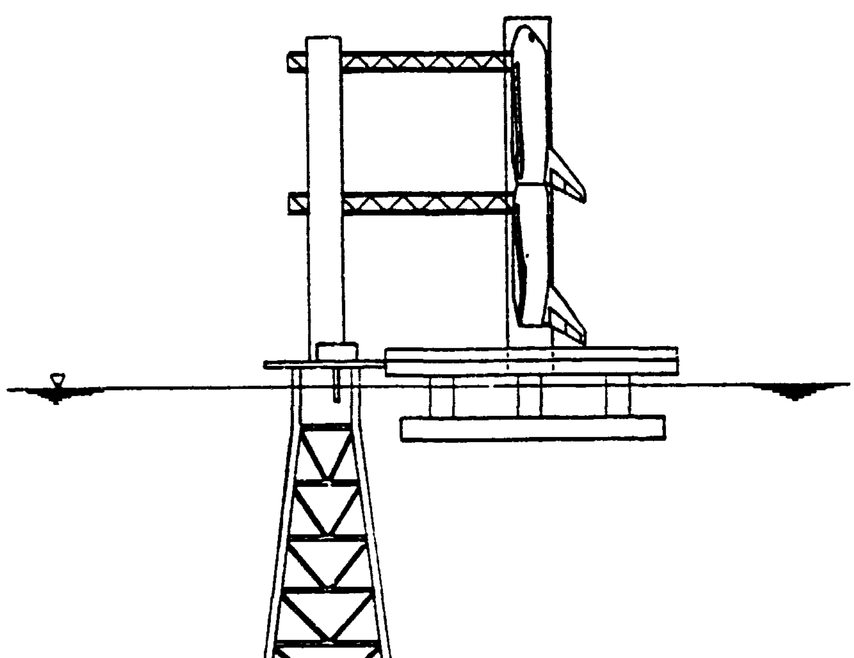

VIEW A-A

FIGURE 4.3 LAUNCH PLATFORM
(VEHICLE ERECTED FOR LAUNCH)

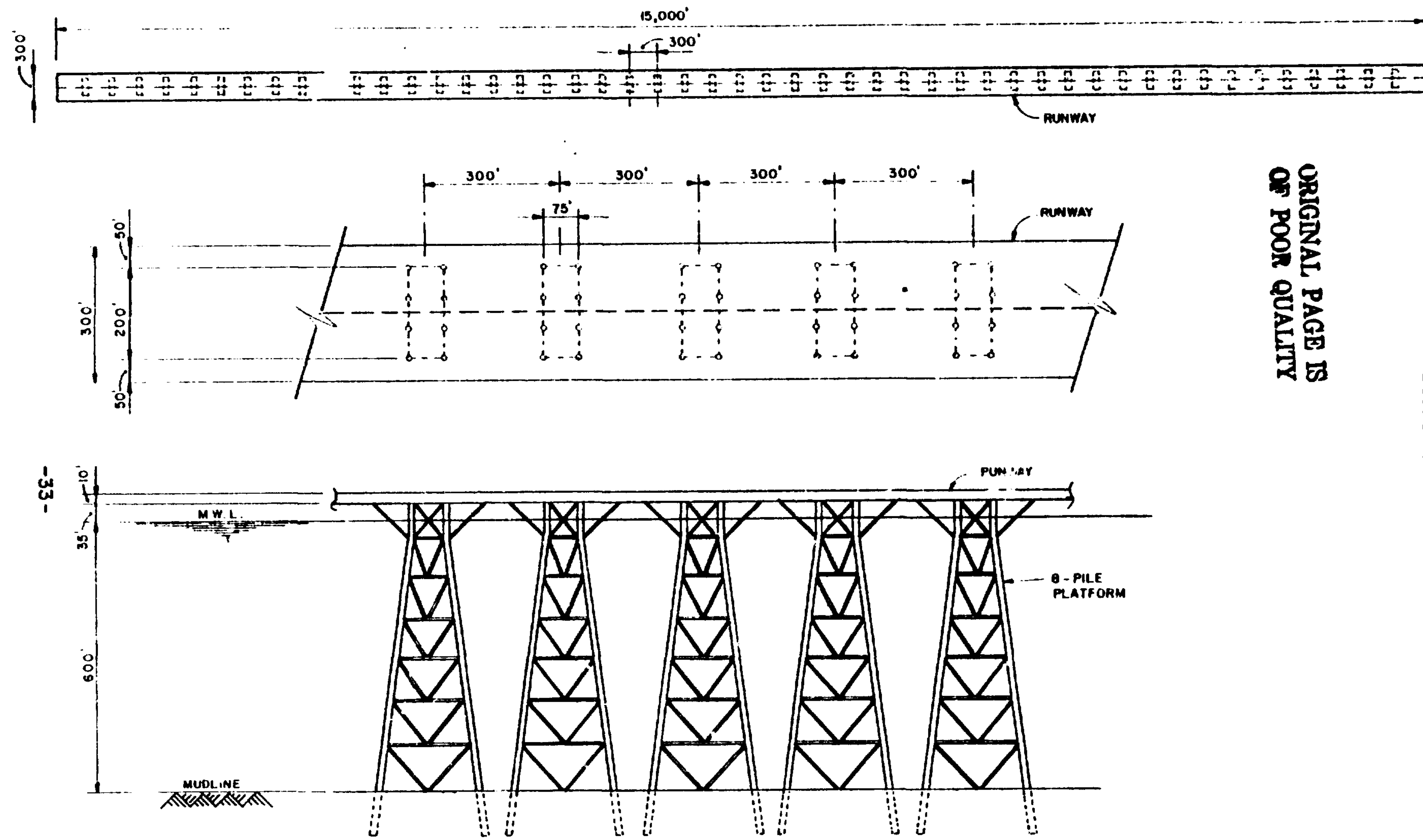

FIGURE 4.4 RUNWAY, PLATFORM STRUCTURE - PILE SUPPORTED CONCEPT

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FIGURE 4.. - OFFSHORE SPACE CENTER - ARTIST CONCEPT

5.0 RECOMMENDATIONS

The U.S.A. needs an independent equatorial launch capability for the stability and economics of our space program. This study is a first cut at estimating costs, configurations, and facilities for an OSC. Further effort to define a preliminary design should be expected to bring to light additional technical difficulties to be resolved.

As a result of the work performed on the conceptual designs and costing of the OSC facilities, several recommendations can be made at this time for additional program efforts.

For NASA to undertake a program to demonstrate the economic viability of the OSC concept in an efficient and timely manner, both development of these concepts and of others (especially hybrids) must be pursued. To examine each concept in terms of producing the most cost-efficient concept should be an objective of further efforts with OSC studies.

5.1 RECOMMENDED CONCEPTS STUDIES

The conceptual design phase of this study only touched on two of the possible concepts to install an OSC facility near the equator. Other concepts, including dynamically positioned semi-submersibles, a shipshape OSC and combinations of concepts may prove to be more economical or desirable operationally.

A need to optimize the structural type of support and thus, the OSC, exists and further studies are required in that area. Current advances in the placing of decks on offshore structures should be investigated for applicability to the OSC in an effort to achieve the most economical system. Other significant developments in the marine industry could be cost effective.

Considerations of shallow or island areas in the equatorial region could require completely different structural concepts and could be even more economical. Possible political problems could, however, be encountered which may greatly influence control and ownership in such areas.

Multiple uses of such a facility should be considered to enhance its efficiency. Intensive and extensive mairculture could be employed in conjunction with an OSC to better utilize this artificial reef and its ocean resources. Adequate warm water year around, low waves, and little seasonal variation would be condusive to such a project. It is unlikely that the area would ever be threatened by a huge oil spill because drilling in the area is nonexistent. Since demand exceeds supply in a market that exists, such mariculture has the potential of changing the world protein supply.

The type of OSC structural and operational concept which is most feasible is entirely dependent on the site selection, its environmental loads and bottom conditions. As future site studies are performed with additional definition, other OSC designs may become feasible.

5.2 RECOMMENDED CONCEPT DESIGN DEFINITION

A conceptual design only was performed on the two proposed support methods during this study. Further structural design efforts on each concept to develop preliminary designs are needed for a better definition of the OSC. A preliminary design effort should address such technical difficulties as the maintaining level of the runway within tolerances to minimize the length required. The straightness of the runway and the ability to withstand the moments reduced must be addressed in a preliminary design effort.

Emergency requirements should be analyzed and considered carefully for impact of a design. Design goals should be established with regard to severe storms and potential reductions in risks achieved through incorporation of appropriate safety systems and procedures.

An optimization of OSC design subsystems would be very beneficial for a clear view of the most economic, operationally acceptable concept. Special attention should be given to critical subsystems such as the launch modules, mooring and dynamic positioning equipment, and to other modules requiring extensive development of technology. A more detailed design synthesis is required to correctly trade-off the different design concepts.

Development of appropriate deployment techniques and detailed cost analyses should be performed. The feasibility of various subsystems should be established and dynamic model testing should be performed.

Through various R&D programs such as these, design data can be developed to ensure a viable OSC facility.

Efforts must be made to locate suitable construction sites, establish the sea bottom topography, obtain soil sample data, and establish the design storm and operating wave conditions.

5.3 RECOMMENDED CONCEPT EVALUATION STUDIES

In order to establish a preferred OSC configuration, an evaluation of other promising concepts is justified. Further study efforts of alternate concepts (which were not within the scope of this program) and a more detailed development of the existing designs are needed to establish an efficient OSC facility.

Trade-off studies on costs, and fabrication, construction, and installation procedures must be made to optimize the OSC design. Environmental and design criteria should be realistically established to reflect study progress. Soil borings to determine bottom conditions and soil properties need to be obtained for further developmental engineering of either a pile-supported OSC concept or a moored OSC concept.

Once preliminary designs are developed for a variety of concepts, then optimization, trade-off, and evaluation phases may be initiated. An evaluation with less data could be meaningless, so one is cautioned about drawing significant conclusions from such. Systems need to be developed so that input could be easily used in

the design trade-offs, i.e. space utilization, loading, systems separation and interaction requirements, and plant layout.

The OSC must be acceptable from technical and financial aspects as well as politically if it is ever to become a reality. A criteria for technical acceptability may include safety, operation efficiency, technical risk, ease of maintenance and probability of need (such as for an SPS project). An acceptability criteria for financial evaluation may include cost versus revenues, accessibility, functionality, and economic impact. Political factors include: ship and air traffic patterns, job impact, pollution impact, and safety concerns of countries nearby would be important criteria for evaluation. A determination of a single OSC facility which is technically feasible and cost-efficient could then be made.

SPS DEVELOPMENT AND OPERATIONS SCENARIO

PURPOSE

This scenario is established as a basis for estimating research, development, investment, and production costs for solar power satellites.

OVERALL PROGRAM SCOPE AND ASSUMPTIONS

The SPS program is divided into four phases:

(1) Research: This phase will address and resolve issues of environmental effects, socio-economic factors, technical practicality and selection of cost-effective technologies, and will develop a comparative assessment of benefits attendant to SPS relative to other energy options. It will be comprised mainly of ground-based research, but certain flight projects are also required to complete the research.

This scenario treats only SPS hardware and software research and research on support technologies such as space operations. Environmental research will be conducted in parallel with the research described herein. Costs and schedules for environmental research are not reflected in this scenario.

(2) Engineering Verification: This phase will bring the technology results of the research phase to a state of large-scale development readiness. This means that prototype subsystems will be developed and tested, as will prototype production and operations processes. The products of this phase will be (a) specification for the demonstration SPS and all its support system; (b) cost estimates for the demonstration and production SPS's and all its support system; (b) cost estimates for the demonstration and production lines; and (c) firm development and risk management plans for the following program phases.

(3) Demonstration: This phase will produce and test a pilot plant SPS that delivers power to a commercial electric power net, in order to demonstrate the operational suitability of SPS's for large-scale baseload power generation.

(4) Commercialization: This phase will have two sub-phases insofar as cost accounting is concerned, investment in production and operations facilities, and recurring production. The investments will be separately accounted, but all investments will be amortized over the cost of production of SPS's. For purposes of this scenario analysis, the production run will be sixty 5-gigawatt SPS's produced at a rate of two per year after the first unit, which will be produced as a prototype in one year.

The following assumptions are employed in the construction and analysis of this scenario.

(1) The commercial SPS's are the DOE/NASA silicon photovoltaic reference system. The main features of this system are:

(a) Silicon solar array without sunlight concentration, employing 50-micrometer single crystal silicon solar cells with 75-micrometer glass coversheet and 50-micrometer glass substrate.

(b) Graphite composite solar array and transmitter support structure.

(c) Electronically-steered phased array microwave power transmitter employing a 10-db truncated Gaussian illumination taper on a 1-kilometer aperture. The power beam is focused at the ground receiver by a spread-spectrum retrodirective active phase control system. The power beam baseband is synthesized from the spread-spectrum uplink, amplified by 70-KW_{RF} klystron power amplifiers, and radiated by a slotted waveguide antenna.

(2) The SPS's are assembled by a construction base in geosynchronous orbit. SPS components and subsystems are fabricated on Earth, shipped to low orbit by HLLV, and transported to GEO by an electronic orbit transfer vehicle (EOTV). Assembly and test of subsystems and components are performed on Earth up to the limits imposed by capabilities of the transportation system.

(3) Space crews are transported to and from low orbit by a modified space Shuttle and between low orbit and geosynchronous orbit by a high-thrust orbit transfer vehicle. Crew duty periods are nominally 91 days, resulting in four crew exchanges per year. The total time spent in space by a crewperson is 95 to 100 days including transportation periods.

(4) Decisions to initiate subsequent program phases are incrementally made as necessary to avoid schedule delays. As an example, if a proto-flight klystron were needed two years into the engineering verification program, its development could be initiated during the research program at such time as a decision between klystrons, magnetrons, solid state, etc., could be made based on research results.

(5) Development costs for potentially multipurpose space systems such as manned OTV's and a reusable Shuttle booster are accounted in this scenario as SPS costs.

RESEARCH PROGRAM

The research program has been presented in detail in the Research Planning Interim Report, Boeing document D180-25381-1, published in July, 1979. Although further iterations and updates on this planning data will be necessary, the plan as represented therein is considered adequate for this scenario. The plan includes over 150 ground-based research tasks, plus certain high-priority flight research tasks:

(1) A large aperture phased array technology satellite (LAPATS).

(2) A beam-builder and solar array deployment test Shuttle flight.

(3) A Shuttle sortie to test plasma effects, including a high voltage solar array test and an electric (ion) thruster test.

Principal decision milestones of the research activity are shown in Figure 1. Detailed schedules supporting these milestones are contained in the referenced document. The schedules upon which these milestones are based were constrained by assumed funding availability . . . the related funding vs time curve is shown in Figure 2.

ENGINEERING VERIFICATION PROGRAM

The engineering verification program has been subjected to less analysis than the other SPS program phases. Typical activities are summarized in Table 1. A comprehensive analysis remains to be conducted.

SPS-3036

FIGURE 1
Research Program Decision Schedule

BOEING

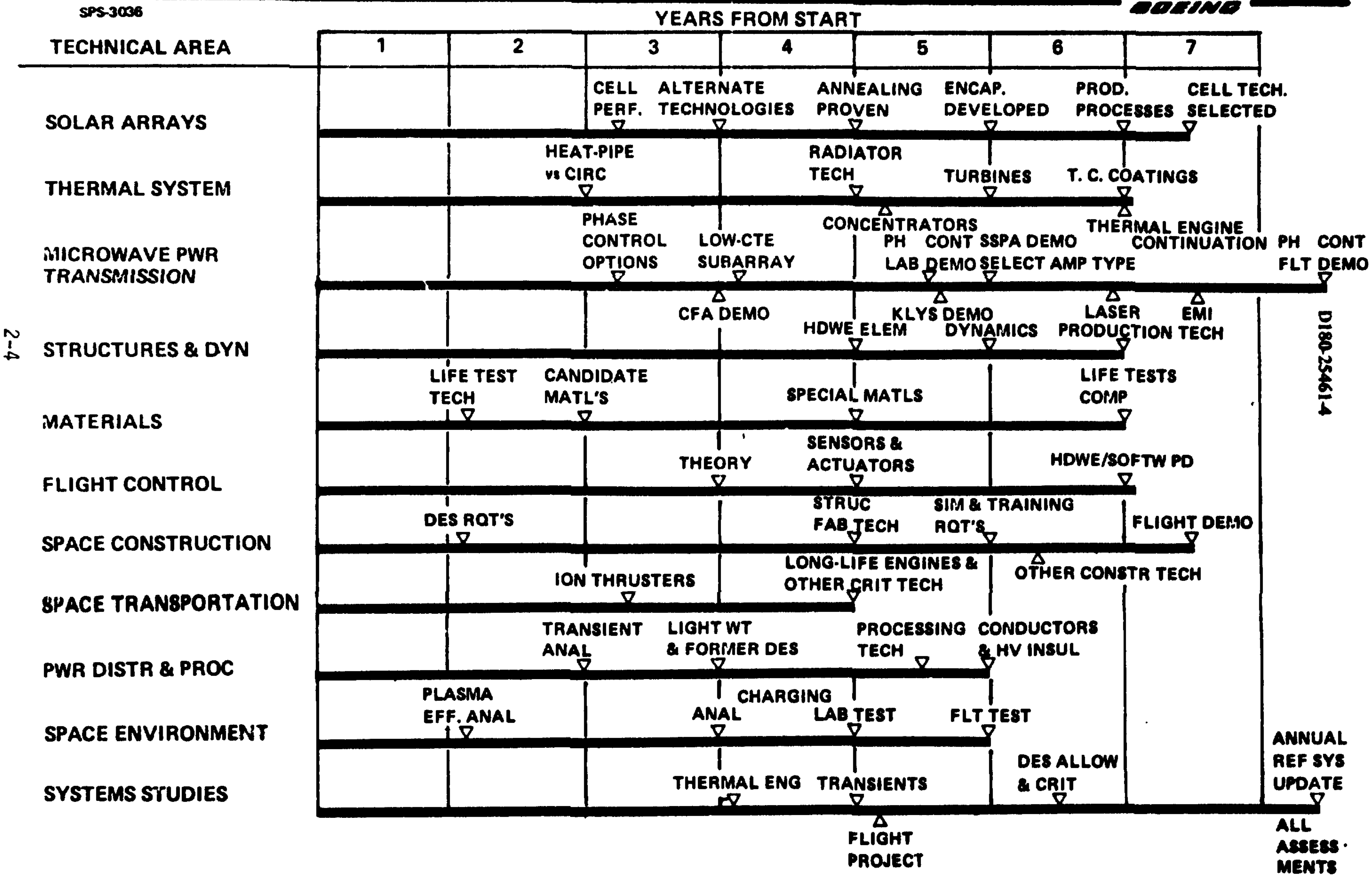

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FIGURE 2

Total Research Program: Nominal Costs

PROJECT 63ER TOTAL CONSUMPTION IS 438443600. DOLLARS

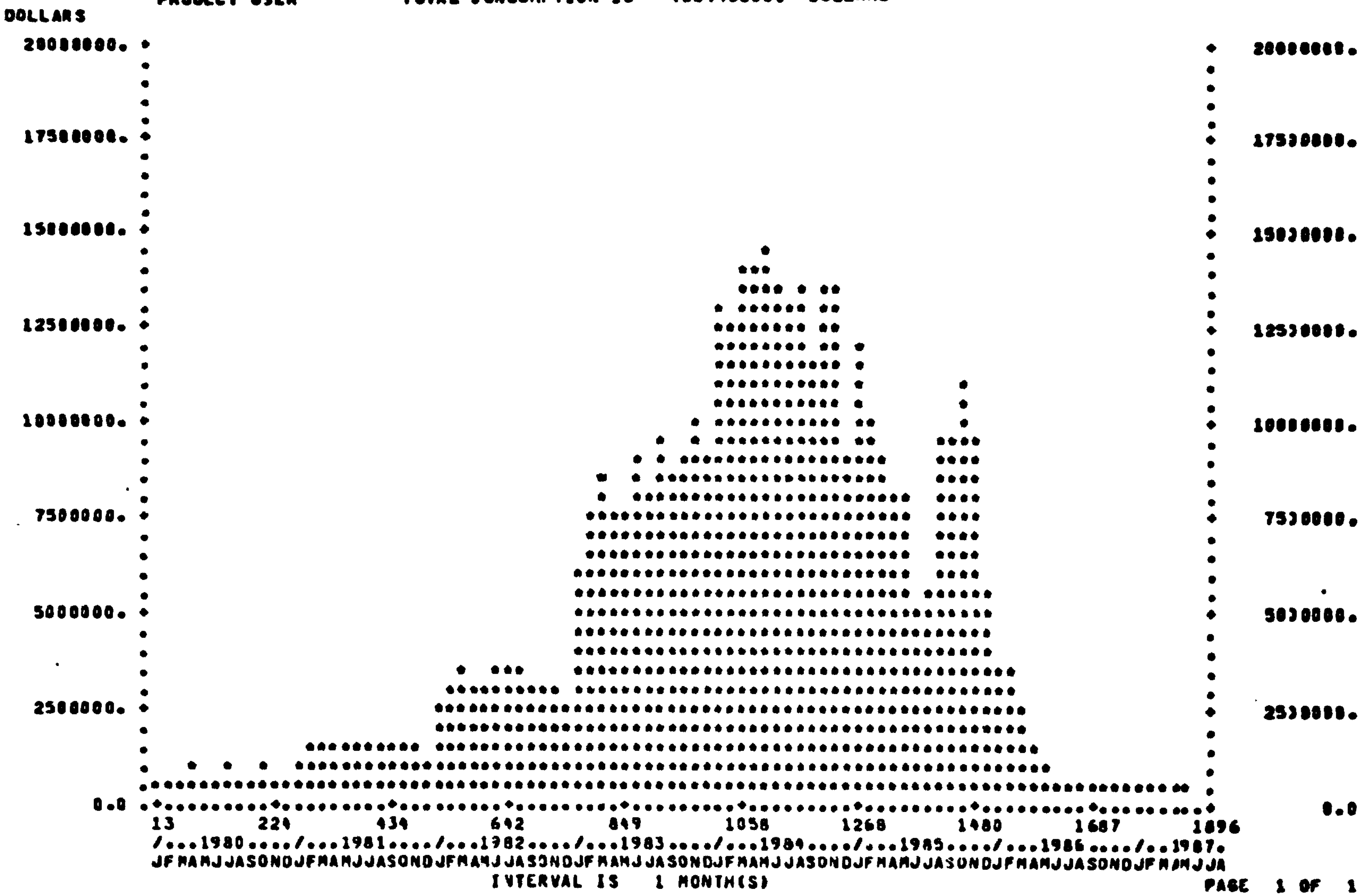

TABLE 1

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

ISSUE		TASK	DURATION (YR)	FACILITIES REQUIRED
1-1	Solar array = cost, quality	Develop and operate pilot production line	6	Production equipment (to be developed) and floor space = 1000 M2
1-2	Solar array packaging and development	Develop packaging and deployment systems; flight test 1-MW array*	5 (2 flight)	LEO Development Lab; Shuttle
1-3	HV solar array operation and degradation at GEO; annealing	o Test array panels at GEO	5	Shuttle; manned OTV
		o Return samples to LEO and anneal	2	Manned OTV and LEO Development Lab
1-4	Solar array design criteria	Analyze results and prepare criteria and specifications	2	None
2-1	Fluid and thermal systems			
	o Heat rejection, - reflectivity	o Lab test prototype hardware elements	4	Existing
	o Fluid containment	o Flight test same	3	Shuttle, LEO Development Lab, Manned OTV
	o Degradation			

* Array to power #3-1 in addition.

TABLE 1 (continued)

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

	ISSUE	TASK	DURATION (YR)	FACILITIES REQUIRED
3-1	Microwave equipment performance and life at GEO	o Design and build proto-flight test hardware	4	Existing
		o Flight test at GEO	4	o LEO Development Lab (test) article assy) o Manned OTV (Transport to GEO and support)
3-2	Microwave/laser equipment cost in production	o Adopt proto-flight designs from #3-1 to production o Amplifies o Phase control circuitry o Phase distribution systems	2	None/Existing
		o Develop and operate pilot production lines	5	Equipment to be developed and floor space (1000 - 2000 M^2)
3-3	Specifications and design criteria	Analyze results of 3-1 and 3-2 and prepare specs and criteria	2	None

TABLE 1 (continued)

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

	ISSUE	TASK	DURATION (YR)	FACILITIES REQUIRED
4-1	Predictability of large space structures dynamics	o Design test large space structure (= 100 x 1000 M)	1	None
		o Conduct dynamics analysis	1	None
		o Fab in space and test	3	Shuttle and LEO Development Lab
4-2	Structural systems' production cost	*Develop and test structural elements pilot production live*	3	Equipment to be developed and = 200 M^2 floor space
5-1	Materials degradation in actual environment	Test materials in GEO environment	5	Shuttle, LEO Development Lab and manned OTV
5-2	Materials production economics	Develop and test pilot production lives for cost-critical materials	4	Equipment to be developed and floor space = 2000 M^2
5-1	Controllability of large structures	Analyze results of 4-1 and develop control hardware	2	None
5-2	Electric thruster/plasma/ magnetic interactions and control influences	o Build and test experiment system at LEO and GEO (combine with 1-2, 3-1, and 4-1)	4 (design and dev.) 2 (flight test)	Space shuttle, LEO Development Lab Manned OTV
		o Analyze control influences	2	None
5-3	Software/hardware QC, QA, redundancy and production cost	Analyze software/hardware and select most economic overall approach	2	None

TABLE 1 (continued)

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

	ISSUE	TASK	DURATION (YR)	FACILITIES REQUIRED
7-1	Crew and equipment productivity	o Examine and test equipment and procedural options during 1-2, 3-1, 4-1, and 6-2. Note that this will increase cost of those programs as necessary to try different things	Per related tasks	Same as related tasks
		o Analyze results and develop appropriate criteria	2	None
7-2	Construction problems	Review problems encountered during 7-1 and modify SPS design to ameliorate	2	None
7-3	Actual construction costs	Perform cost analysis based on 7-1 and 7-2	1	None
8-1	Space transportation costs	Analyze shuttle experience and project to HLLV hardware designs and operational environments	2	None
8-2	Electric thruster clustering and plasma drift currents	Conduct cluster test at LEO	4 (Design and dev.) 1 (Test)	Shuttle and LEO Development Lab

TABLE 1 (continued)

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

	ISSUE	TASK	DURATION (YR)	FACILITIES REQUIRED
8-3	Booster engine costs	Breadboard booster engine	4	Engine test facility similar to old F-1 stands
8-4	Crew provisions and cabin designs for large numbers of passengers	o Design and build mockups	2	
		o Conduct simulations	1	Simulation lab (ground-based)
		o Analyze results and develop design criteria		
9-1	Power processor and circuit breaker performance, mass, life, and cost	o Design and test proto-flight power processors and circuit breakers	3	Electric power lab
		o Estimate costs in production environment	1	
9-2	Space environment effects on cable insulation materials	o Conduct thermal/VAC/UV chamber tests	2	Thermal-VAC combined environment lab
		o Conduct tests at GEO in conjunction with 5-1	5	Shuttle, manned, OTV

TABLE 1 (continued)

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

	ISSUE	TASK	DURATION (YR)	FACILITIES REQUIRED
9-3	Plasma and breakdown design criteria	o Conduct lab tests of conductors, insulators, and standoff	4	Combined environments
		o Conduct LEO/GEO tests of proto-flight hardware with 1-2, 3-1, etc.	4	Shuttle, LEO Development Lab, and Manned OTV
10-1	Electric Thruster plasma effects of magnetosphere	o Conduct thruster tests at selected altitudes	1	Shuttle and manned OTV
10-2	Solar array degradation during transfer	o Conduct array tests at selected altitudes	1	Shuttle and manned OTV
10-3	Shuttle/OTV/HLLV effect on upper atmosphere and ionosphere	o Observe and analyze effects of shuttle and OTV burns and extend by analysis to HLLV levels	2	None (no special flights required)
10-4	Environment-related design criteria	Analyze space environment results and develop criteria	Level of effort during this phase	None

TABLE 1 (continued)

REPRESENTATIVE ENGINEERING VERIFICATION ACTIVITIES

	ISSUE		TASK	DURATION (YR)	FACILITIES REQUIRED
11-1	Integrated estimate of production SPS design and cost		Analyze all results, update and maintain design and cost data	Level of effort during this phase	None
11-2	Final plans and specs for demonstration system	o	Phase A demonstration	1	None
		o	Phase B/C demonstrator and support systems	3	Office Space
		o	Conduct SR&T as required to support design decisions	3	Office and lab space

It is evident from the flight experiments included in Table 1 that a substantial level of flight activity will be required to develop the operational processes and procedures that will comprise SPS space operations. Present estimates indicate need for a manned space laboratory in low Earth orbit and a manned orbit transfer vehicle capable of occasional manned geosynchronous orbit operations. These elements are major cost items in the engineering verification program.

A preliminary schedule for the engineering verification program is presented in Figure 3. This schedule assumes that development of the space laboratory facility and manned OTV can begin during the research program; these developments are the critical paths in completing the engineering verification program.

For the purposes of this scenario analysis, the development costs of the space laboratory and the manned OTV are assumed charged to the SPS program, although these support systems will undoubtedly serve diverse needs. It is assumed that an unmanned OTV is developed for other purposes earlier than the engineering verification program. Delta costs to upgrade it to a manned OTV are grossly estimated at one billion; the costs for the space laboratory (development and launch but no operations) are taken as an assumptional $3 billion.

ENGINEERING VERIFICATION FLIGHT PROJECTS

Several of the verification test tasks from Table 1 were merged into a flight project designated "Engineering Verification Test Article" (EVTA). These tests result in a set of requirements for this flight project as summarized in Table 2. These requirements were utilized to develop the conceptual configuration shown in Figure 4.

The EVTA will be assembled at the LEO development lab (LDL) in two major parts: (1) the solar array and its support structure combined with electric propulsion test hardware, and (2) the transmitter. The solar array and electric propulsion equipment will be tested at LEO and two intermediate altitudes for degradation, plasma effects, and thruster plume/magnetosphere interaction. This assembly will be transported incrementally to the intermediate altitudes and to GEO by the manned OTV operating in an unmanned, low-thrust mode. Intermediate altitude tests will require an estimated one to three weeks each.

FIGURE 3
ENGINEERING VERIFICATION PROGRAM SCHEDULE

SPS-3047

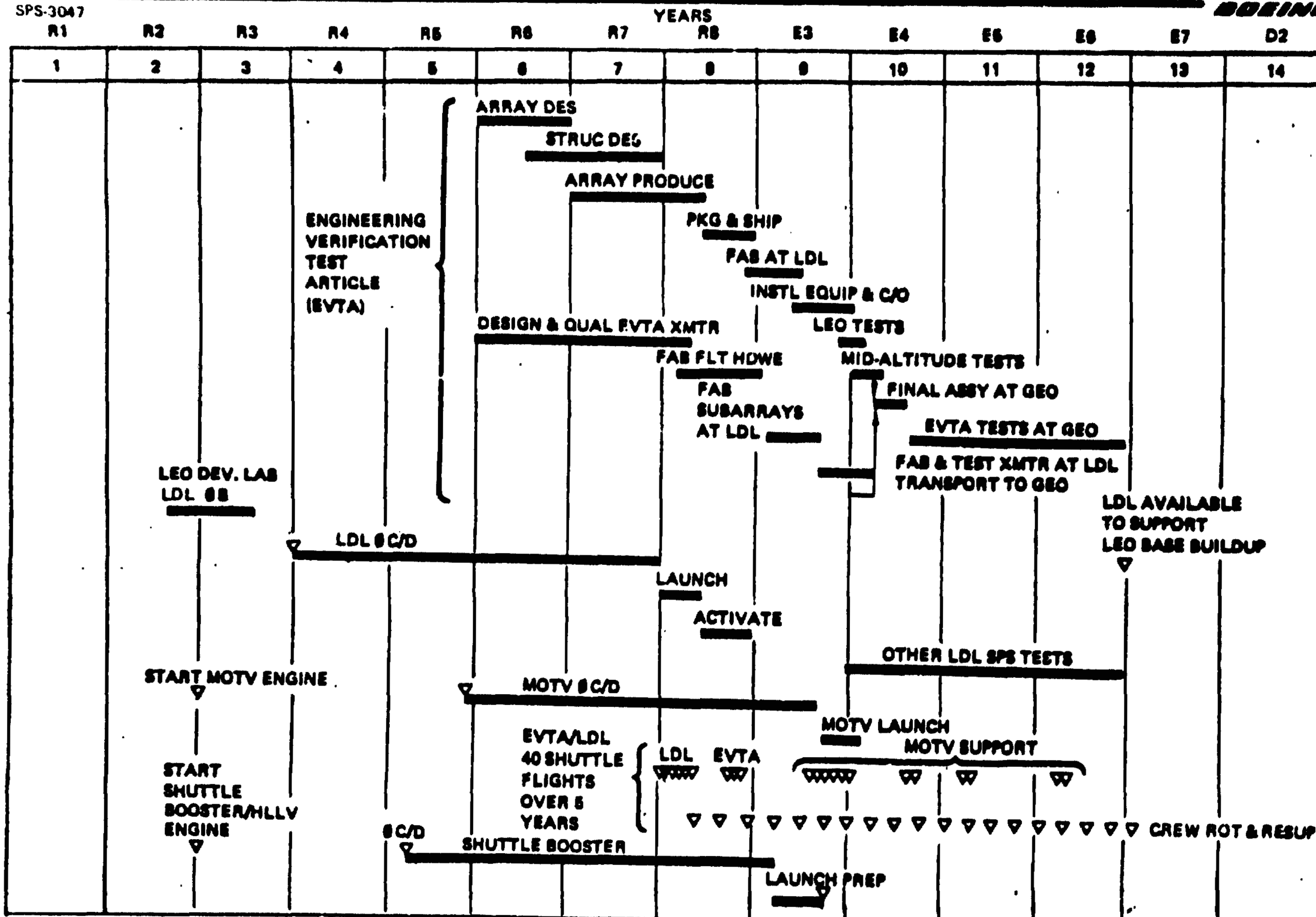

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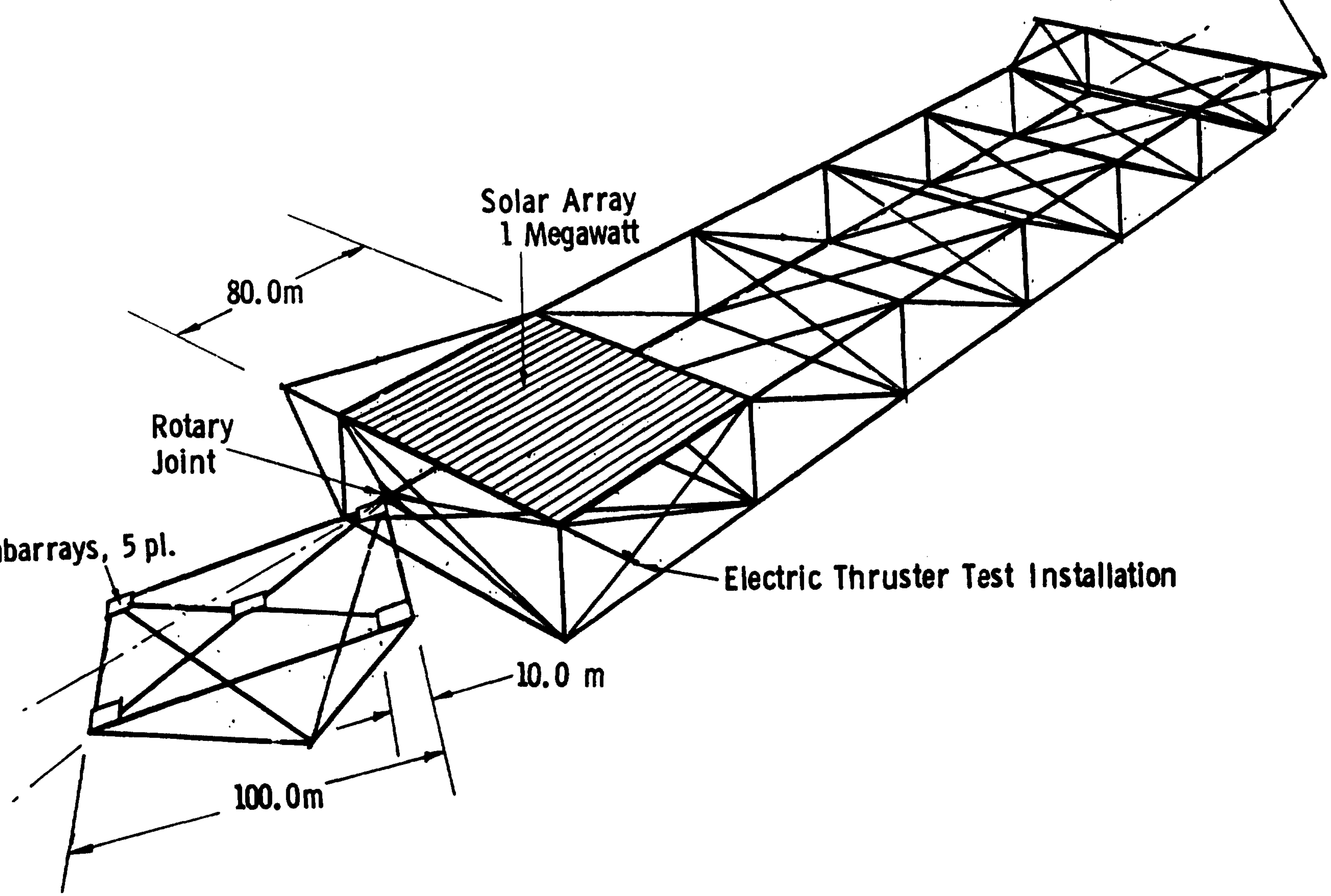
TABLE 2
ENGINEERING VERIFICATION TEST ARTICLE (EVTA) REQUIREMENTS

- 1-Megawatt Solar Array (or more)
- Test Array Panels at GEO--Return samples to LEO
- Test Proto-Flight Microwave Equipment at GEO
- Test Large Space Structure 100 x 1000 m
- Test Materials at GEO
- Experiment with Assembly Techniques
- Test Power Processors and Cables
- Test Plasma and Breakdown
- Conduct Thruster and Array Tests at Selected Altitudes

FIGURE 4
ENGINEERING VERIFICATION TEST ARTICLE CONCEPT



The transmitter will be assembled and tested at the LDL and then delivered directly to GEO by the MOTV (unmanned). Final assembly of the transmitter to the solar array subassembly will be assisted by a manned OTV flight to GEO with a GEO stay of about two weeks. Manned sortie visits to the EVTA at GEO are assumed after 6, 12, and 24 months of testing (see Figure 3).

Additional test requirements for the LDL were derived from Table 1. The total set of SPS engineering verification test requirements levied on the LDL is summarized in Table 3. It is assumed that tests not directly supportive of the EVTA are deferred until transportation of the EVTA to GEO begins.

Preliminary estimates indicate that an LDL crew of 8 will be adequate to conduct the engineering verification flight tests and support MOTV operations. The LDL should provide additional transient crew quarters for up to four MOTV crewpersons.

DEMONSTRATION

The present SPS program concept presumes that the engineering verification phase of SPS will be followed by a demonstration phase with the objective of demonstrating operational suitability of SPS for commercial use. Demonstration concepts for SPS have been studied over the past several years. A number of flight vehicle configurations have been developed. Several issues have surfaced, and provide a judgment as to the objectives of a demonstration system:

- o Successful completion of the research and engineering verification phases of SPS should provide unprecedented technical and cost confidence.
- o If a utility company acquires an expensive powerplant that fails and cannot be readily restored to service, the financial consequences are severe.
  - o The demonstration system should therefore demonstrate operational suitability of SPS: Grid compatibility, availability, and repairability. Enhancement of cost and technical confidence will also result.

Based on these considerations, a set of provisional requirements for an SPS demonstrator have been developed. First, it must operate at geosynchronous orbit. This is important

TABLE 3
LEO DEVELOPMENTAL LAB TASKS

- Deploy 1-MW EVTA Array
- Conduct Annealing Tests on Irradiated Solar Array Panels
- Test Thermal Fluid Systems
  - Coating Degradation and Restoration
  - Fluid System Assembly, Charging, Repair
- Assemble EVTA Subarrays, Test, and Install Subsystems and Equipment
- Assemble and Test EVTA Structure
- Develop Assembly and Installation Techniques and Tools
- Conduct EVTA-associated LEO Electric Thruster Tests
- Develop Construction/Maintenance Crew Operations Procedures
- Checkout EVTA Elements (Array, Auxiliary Equipment, Transmitter) and prepare for shipment to GEO

because the ionizing radiation and plasma environment in geosynchronous orbit is significantly different from that at low Earth orbit. Also, a geosynchronous location is essential in order to provide continuous operation with a ground receiving station.

Secondly, meaningful power must be provided to a utility grid in order to demonstrate operational suitability for baseload service. This means at least ten megawatts.

A conclusive demonstration of reliable control of the power beam and its sidelobes is important to a final demonstration of environmental acceptability as well as showing suitability for continuous service.

The SPS demonstrator should show the capability of an SPS to deliver a high plant factor in the range of 0.8 to 0.9 or better. Achievement of a high plant factor is critical to the economic acceptability of a high capital cost, low fuel cost, renewable energy system.

It is clear that reliable and repeatable startup and shutdown is important. In the process of demonstrating this and the other objectives, SPS hardware and operations can be qualified for commercial service.

Finally, in order to demonstrate the ability of an SPS to provide a high plant factor over a long period of time, maintainability and repairability of the SPS should be included in the demonstration program.

The increasing definition of SPS hardware elements by the ongoing system definition studies has led to the considerations listed below. Of particular importance is the minimum power density achievable with the reference system design. It seems appropriate for a demonstrator system to consider a uniform antenna illumination since the relatively higher sidelobes of the uniform illumination will still be considerably less in intensity than the sidelobes of the operating SPS. It is also clear that a large transmit aperture is needed in order to provide a beam diameter at the ground commensurate with a reasonable rectenna size.

- o Large antenna apertures are required to achieve reasonable beam footprint.
- o With reference SPS klystrons and subarray size 650 W/M^2 is minimum power density. (1 klystron per subarray)

- o Solid-state options less clear, but comparable.
- o Desire 1 MW/CM^2 to drive antenna.
- o Leads to 300-600 megawatts RF power as minimum; roughly size of reference EOTV.

Beam patterns were computed for the minimum power constant illumination transmitter with an 800-meter aperture. The central beam strength is approximately 1 milliwatt per square centimeter, sufficient to drive a rectenna, albeit not at high efficiency. The first sidelobe slightly exceeds 10 microwatts per square centimeter with the other sidelobes at lower levels. Figure 5 shows the received intensity.

Shown in Figure 6 is the beam efficiency as a function of rectenna radius. The right hand scale shows incident power on the rectenna as a function of radius. With an expected rectenna efficiency of roughly 75% to 80% at these power levels, 50 to 100 megawatts can be provided with a relatively small rectenna. This system, therefore, would meet the objectives of the demonstration of SPS in providing sufficient power to a utility grid to demonstrate operational suitability.

The solar array output power required to drive this system is in the range of expected power levels for the electric orbit transfer vehicles. Thus, it is conceivable that initial experimental EOTV's could be constructed at low Earth orbit, used to transport SPS hardware to geosynchronous orbit, and then used to drive the demonstrator system. At the conclusion of the demonstration program, these EOTV's could then be refurbished and placed back into electric orbit transfer service.

Based on the above considerations, a series of program assumptions have been developed:

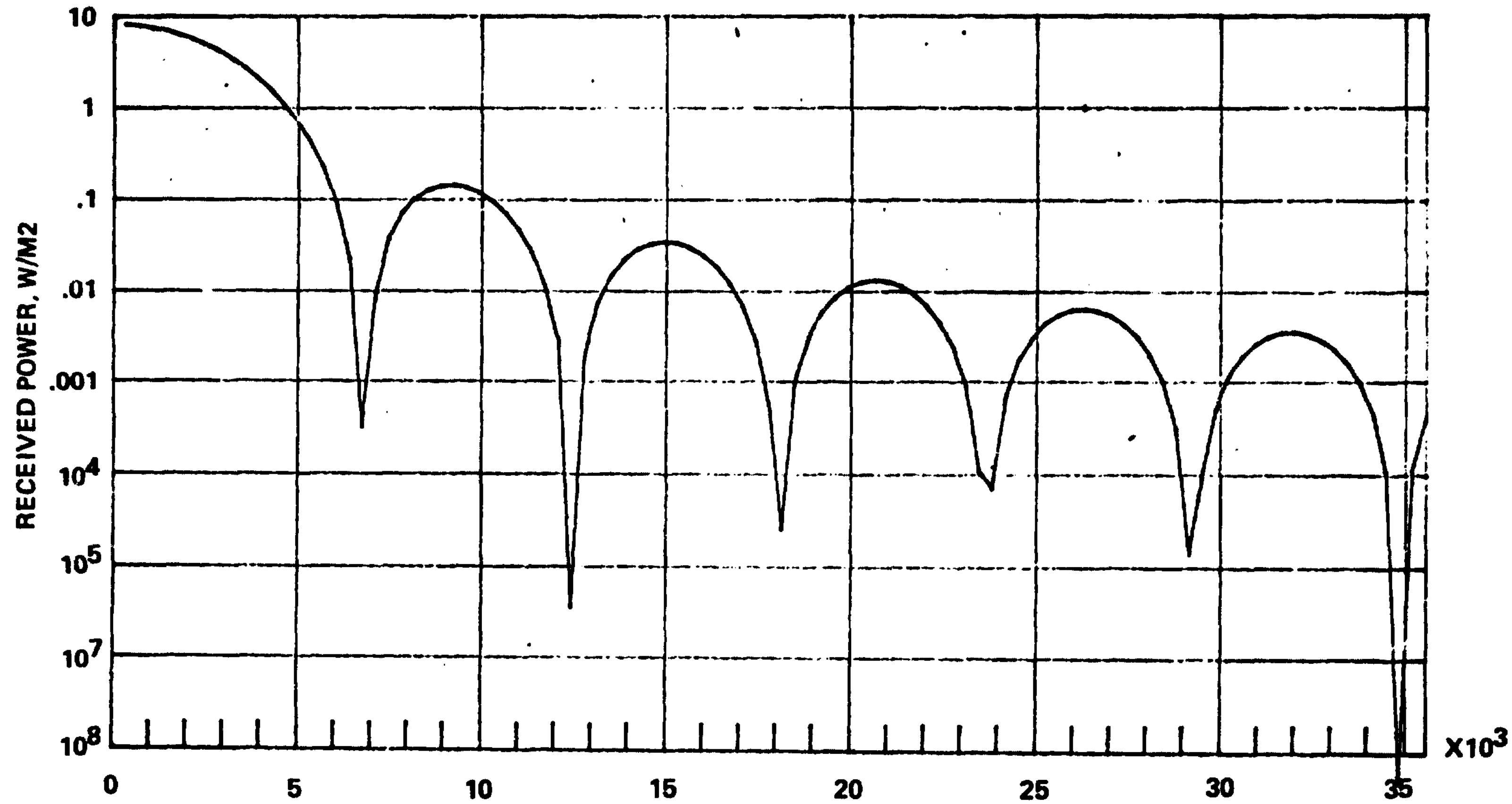
- o A Shuttle-derived HLLV will be available to support the demonstration program. Its payload mass will be about 100 metric tons and volume about 8 x 20 meters.
- o The LEO base will be established as required to support construction of four EOTV's per year. Two EOTV's will be built the first year and four per year thereafter. (See Figure 9.) The commercial production program will begin with 14 EOTV's, reaching full fleet capacity about 2 years into commercial production.

FIGURE 5

Received Power: 650 W/M2, 800-M Aperture
(RF Power = 327 MW)

BOEING

SPS-2973



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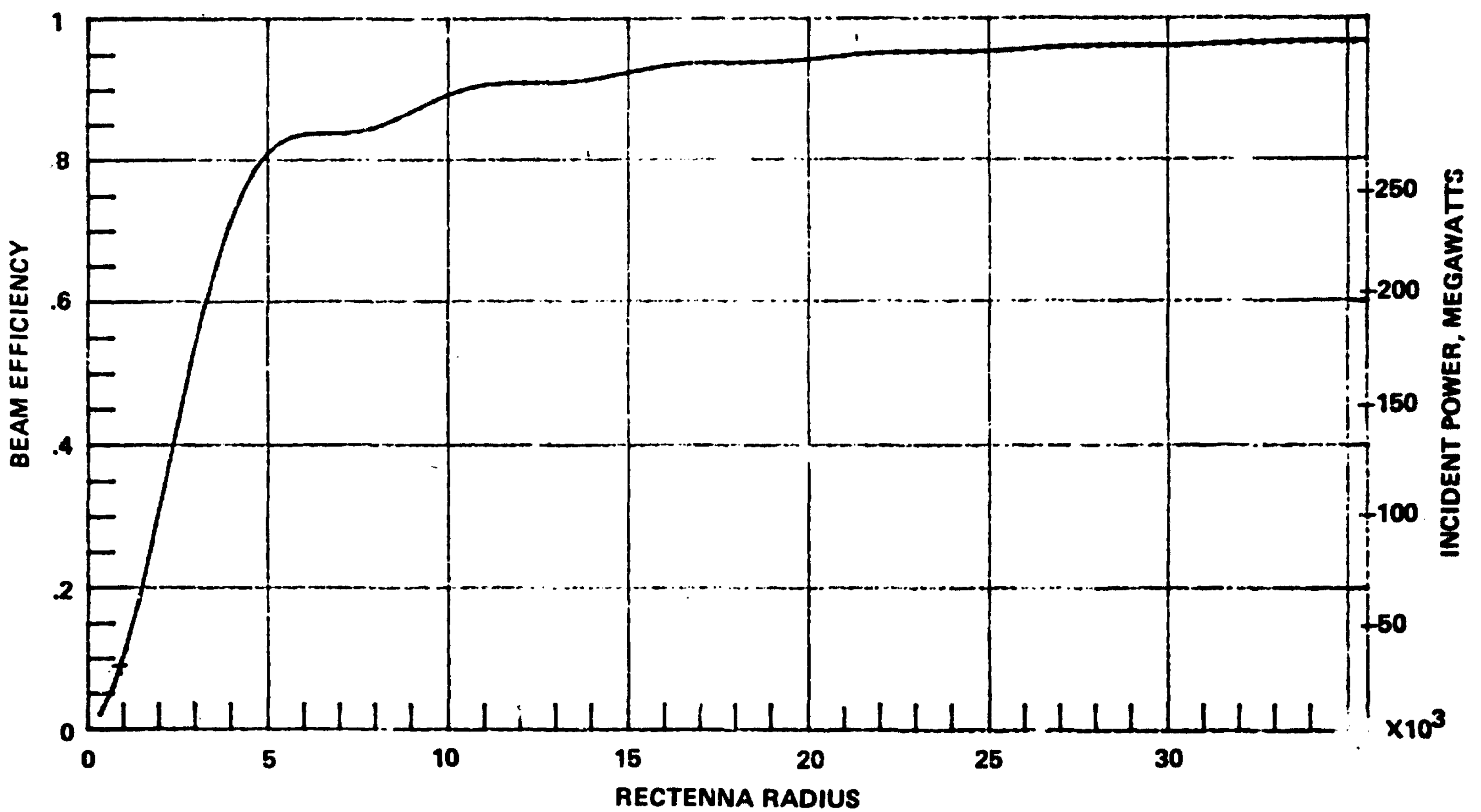
SPS

SPS-2974

FIGURE 6

Received Power: 650 W/M2, 800-M Aperture

BOEING



- The HLLV will be available to support commercial production.

- The demonstrator transmitter will be powered by two EOTV's retained at GEO for that purpose. These will nominally be EOTV's #1 and #2. Two EOTV's are sufficient even if not annealed.

- There is a severe problem with packaging volume of the demonstrator subarrays. Accordingly, they will be assembled at LEO. Assumptions are as follows:

  - Waveguide assemblies will use panel and extrusion construction as illustrated in Figure 7.

  - Subarray mounted phase controls and data circuits shipped as a tested subassembly with all harnesses.

  - Subarray electrical junction box shipped as a tested subassembly.

  - Klystron and preamp shipped as a tested subassembly with all instrumentation and hookup cables.

  - Distribution waveguides shipped separately.

  - Klystron thermal control shipped separately.

  - The assembly sequence is shown in Figure 8.

- The initial GEO base will be designed to support only final assembly and test of the demonstrator. Table 4 summarizes assembly and test sequence.

- LEO and GEO base buildup will support initial commercial production.

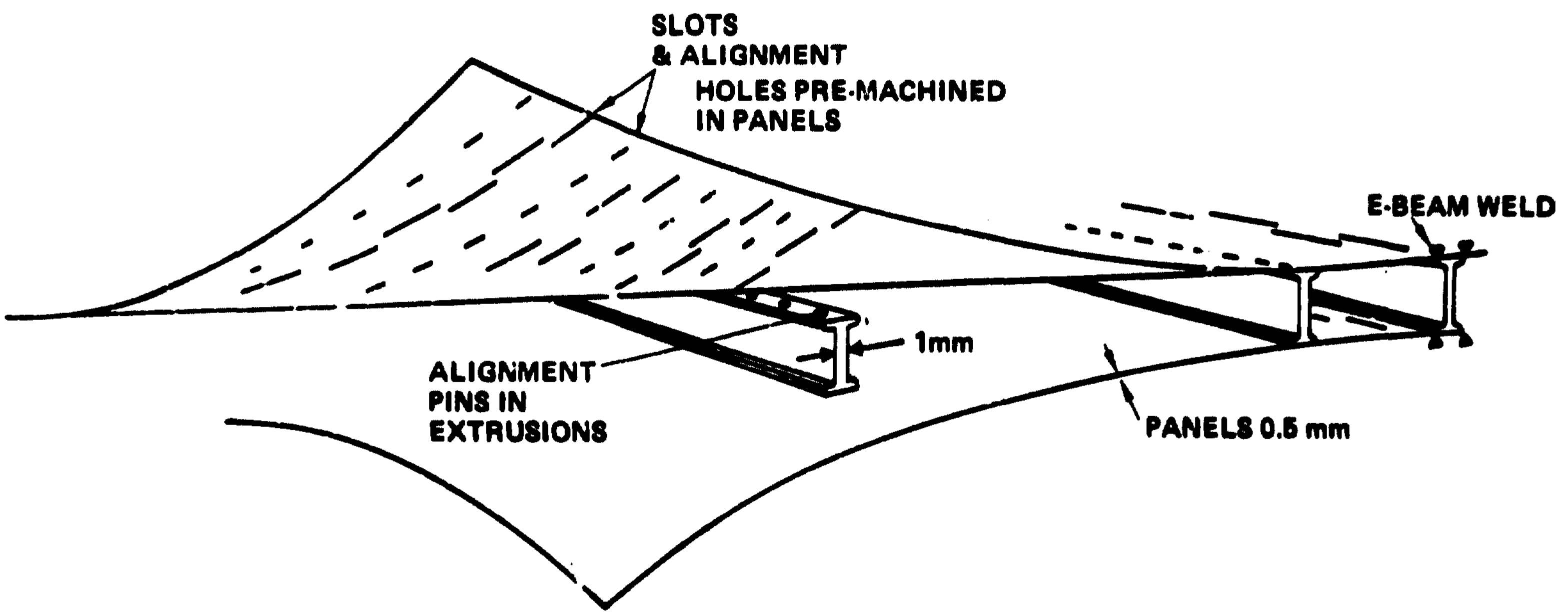
- First commercial (5-GW) will be constructed in one year.

- Subsequent commercial production will be two 5-GW SPS per year for a total program [illegible] SPS's.

- SPS maintenance capability will be built up as needed.

FIGURE 7

Space-Assemblable Waveguide Concept*



*INVENTED BY DAVE LUNDEN

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FIGURE 8
Subarray Assembly & Test

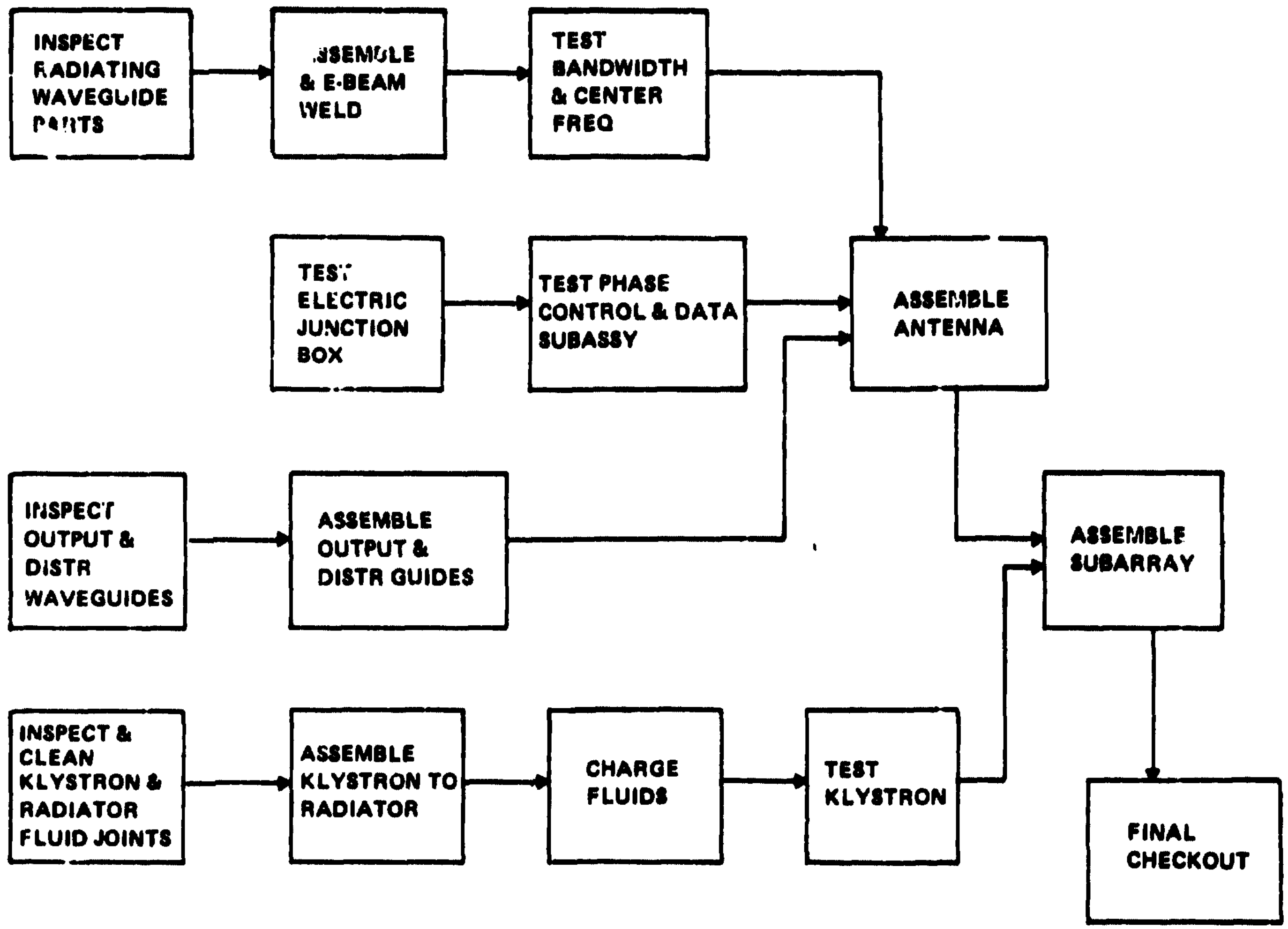


TABLE 4

PROTOTYPE FINAL ASSEMBLY

- Formation Fly 2 EOTV's in gravity gradient stable attitude off sun - maneuver on chemcial propellant
- Small array provides housekeeping power
- Affix berthing cables - 1 day
- Remove electric propulsion installations at berthing points - 1 week
- Reel up cables - 1 day
- Make structure connections and install by flying MRWS - 5 days
- Connect extra bussing and reconfigure electrically - 10 days
- Maneuver to base and berth - 2 days
- Structurally connect antenna - 5 days
- Build transmitter structure and install all subsystems - 9 months
- Electrically connect antenna - 5 days
- Run off-sun tests (passive) - 12 weeks
- Maneuver to sun - 4 hours
- On-Sun checkout - 12 weeks
- Operational Tests - 2 years

MERGED SCHEDULES AND OVERALL SPS DEVELOPMENT

The research, engineering verification, and demonstration schedules were merged by connecting them at critical path points. The relevant junctions between the research and engineering verification schedules are:

- o Solar array production process selected so that EVTA array production may begin (it is assumed that the EVTA array production will not be highly automated and can begin using the experimental production facilities of the research program).

- o MPTS power amplifier selected so that design and qualification of the EVTA transmitter may begin. It is assumed that the EVTA transmitter will incorporate proto-flight designs of basic hardware developed during the research program. EVTA qualification will be sufficient to ensure flight testability and flight crew safety.

The junction between the engineering verification and demonstration programs is that point at which the LDL is through with engineering verification testing and can begin assembly of the demonstration phase LEO Base.

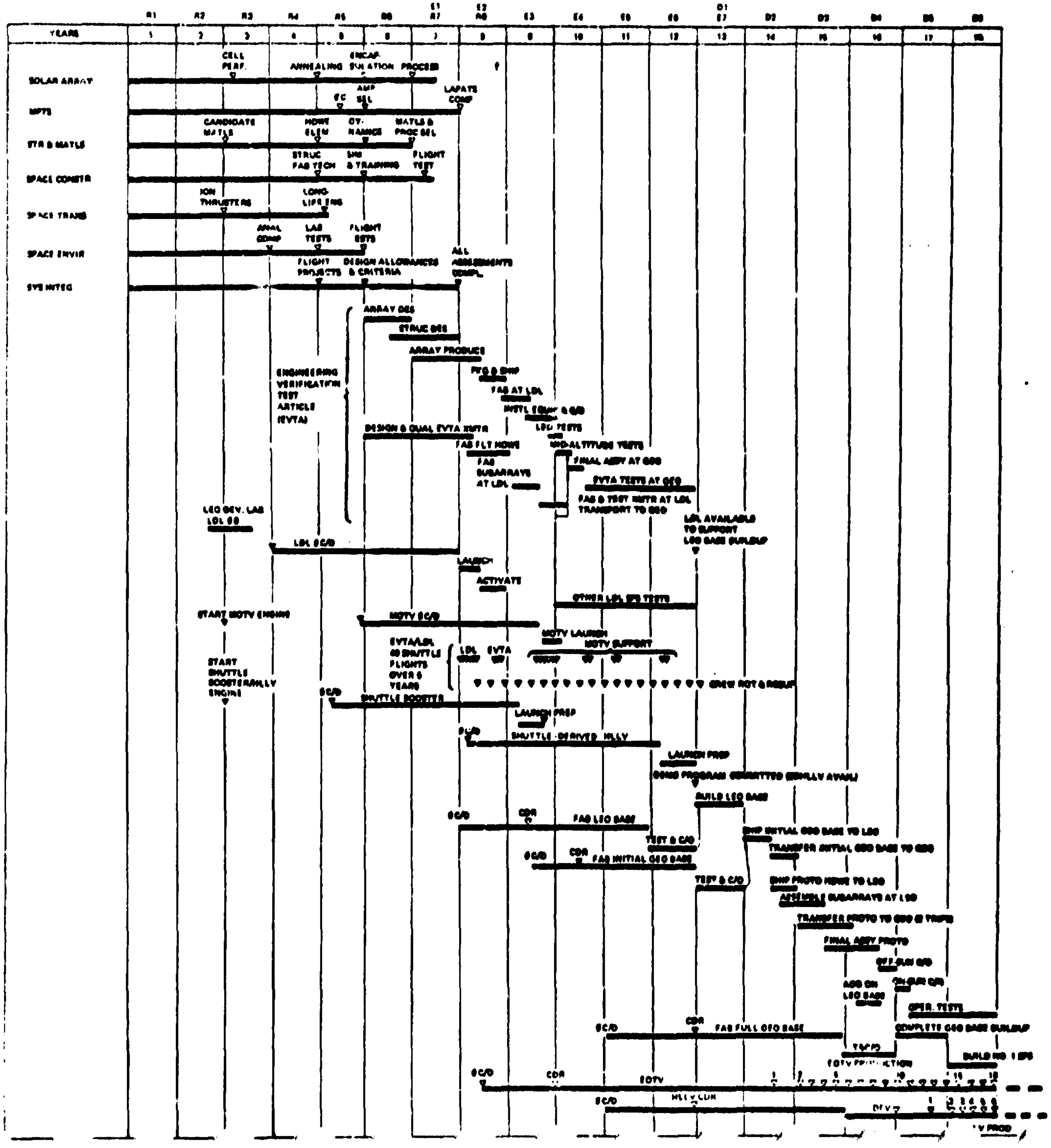
The resulting integrated schedule is shown in Figure 9. Approximately 18½ years is required from initiation of the research program until the 5-gigawatt SPS prototype goes on line.

Accomplishments and Decisions

The decision to initiate each program element actually begins with the budget cycle for the fiscal year in which the element is to be a new start. For purposes of this scenario, and under the assumed aegis of an integrated SPS program, it is assumed that Phase B studies can be conducted without new-start authority.

From budget cycle initiation to award of a Phase C/D contract requires a minimum of about 18 months, sometimes longer. Figure 10 compares major program accomplishment

FIGURE 9
MERGED SCHEDULE



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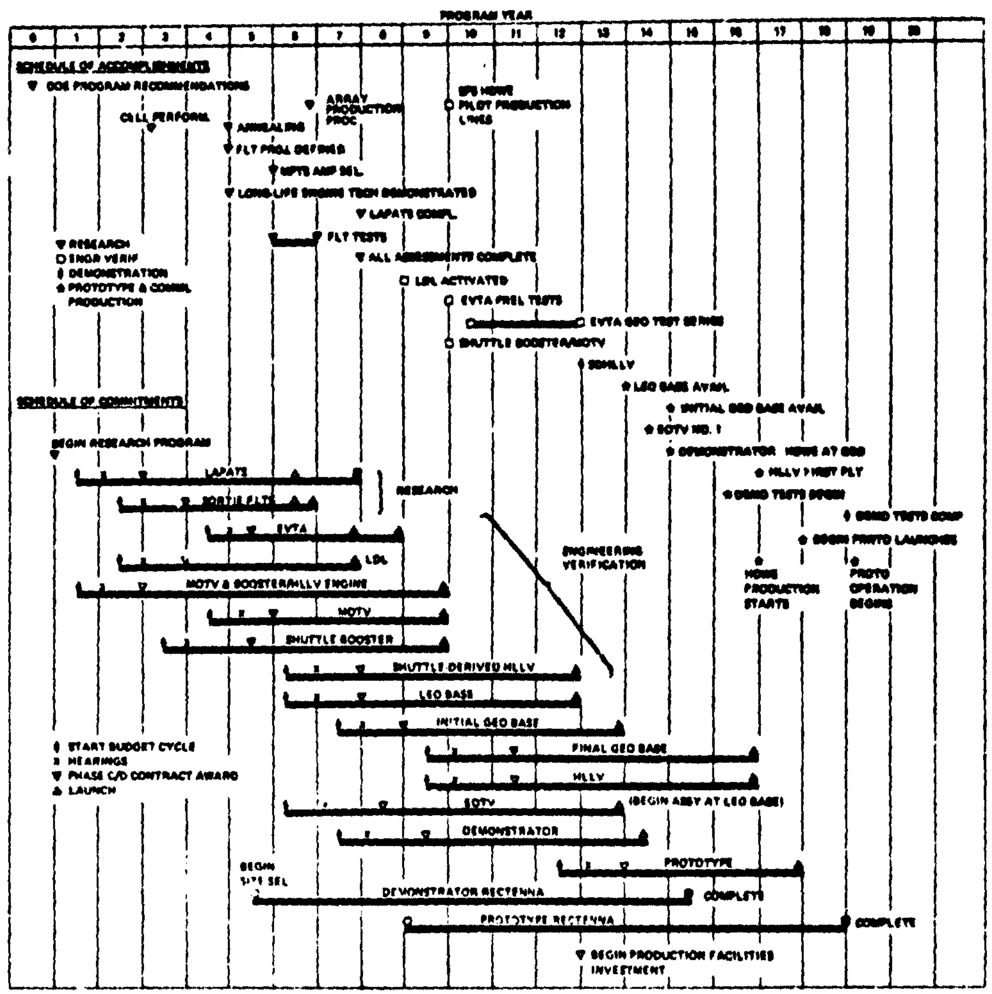

milestones with new start commitments for the 18 new start items that were identifiable on the integrated schedule. If the research program is initiated in 1981, as seems likely, then Year 1 is 1981, etc., with Year 20 being the year 2000. A numbers of observations can be made:

(1) The budget cycle for the manned OTV engine and Shuttle booster/HLLV engine must begin in the year the research program is initiated. (The Shuttle booster was scheduled to support initial manned OTV launch; this may not be necessary.) Accordingly, it may be desirable to fund these engine programs incrementally, initially under a technology aegis.

(2) The LEO Development Laboratory (LDL), which is on the critical path, must begin budget cycle in Year 2.

(3) Budget cycles for big-ticket items (ELO Base; Initial GEO Base; HLLV) need to begin at about the time the research program is complete. At this point the engineering verification program has been initiated and the LDL is nearing initial launch.

(4) Commercial investments in production facilities need to begin about six years before the demonstration test program is complete. Accordingly, one may presume that some sort of risk guarantees may be needed.

(5) Each of the 18 new start items represents an opportunity for major program review and assessment on the part of the Agencies, the Administration, and the Congress.

(6) It appears evident that a continuing, integrated planning and assessment activity should be part of the overall SPS program.

High Risk Options

(1) The research program can be shortened by about a year by greater front-end funding.

(2) A duplicate LDL could be built to advance initiation of the prototype. About three years could be saved, but the prototype design would be complete before any results became available from demonstration system space construction or testing.

(3) A more straightforward high-risk option might be to eliminate the engineering verification phase; about 5 years could be saved according to the schedules as laid out. Problems encountered in the prototype program, however, might result in less overall schedule compression than this estimate.

Low-Risk Option

The least risk option would require each phase to be complete before initiating the budget cycle for the following phase. The respective end-to-end lengths of each phase are: Research, 7 years; Engineering Verification, 11 years; Demonstration, 12 years; Prototype, 10 years. Thus this low-risk option would require a total of 40 years to get the 5-gigawatt prototype on line!

7.1 TECHNOLOGY ADVANCEMENT, DEVELOPMENT AND FACILITY REQUIREMENTS, MICROWAVE POWER TRANSMISSION

In the following the technology advancement requirements will be identified for the Space and Ground segment of the Microwave Power Transmission system. The covered subsystems include all microwave elements of the space antenna with the exception of the receiver-phase conjugator-transmitter circuits and all the elements of the rectenna.

7.1.1 Technology Development Tasks for Space Antenna and Associated Microwave Transmission System

Seven major technology development tasks have been identified in this area. These are listed in Table 7.1-1. Six of the tasks are related to the baseline SPS design, one (No. 6) is concerned with an alternative phase control system.

Table 7.1-1. Technology development tasks for space antenna and associated microwve tranmission system.

NO.	DESCRIPTION	CRITICAL	DESIRABLE	LEVEL OF INITIAL EFFORT (MAN MONTHS)
1	LINE SOURCES (W.G. STICK) AND ASSOCIATED W.G. POWER DIVIDER CIRCUIT ELEMENTS	X		60
2	RF DIXPLEXER	X		30
3	IF DIPLEXER		X	30
4	PHASE DISTRIBUTION CABLE		X	4
5	RECEIVER AND CONJUGATOR SYSTEM	X		80
6	TRANSMITTER PHASE CONTROL SYSTEM	X		30
7	MONITOR/CONTROL NETWORK		X	6
8	PHASE COMPUTING PHASE CONTROL SYSTEM		X	12
9	PILOT TRANSMIT STATION	X		6
10	SPACE ANTENNA WITH SOLID STATE TRANSMIT SOURCE			6
				264

The purpose of these developments is to achieve the design goals for the various components as they are detailed in the Part 3 final report (General Electric Space Division, 3.7.78) and Part 4, Phase 1 final report (General Electric Space Division, April 1979).

The key issues related to the space antenna technology are:

- o Establishment of required amplitude and phase distribution over the antenna aperture.
- o Control and maintenance of these distribution within specified error boundaries.
- o Minimization of structural weight, complexity erection and maintenance needs.
- o Achievement of availability in the given thermal environment and power level range over the specified 30 year lifetime.

The goals for the phase and amplitude errors are listed in Table 7.1-2.

The availability goals for microwave power transmission system between rotary joint of space antenna to klystron input is shown on Figure 7.1-1, while for the complete space antenna it is given on Figure 7.1-2.

More definition of technology development tasks are described in the attached "SPS research planning detailed work sheets."

Table 7.1-2. Systematic and random amplitude and phase error goals for microwave power transmission system of space antenna.

SYSTEMATIC ERRORS FOR 3 LAYERS PHASE DISTRIBUTION

POINTING ERRORS (DEG.)

Source		1 Pilot Station	3 Pilot Station
Doppler ($i = 2.2^{\circ}$, $r_{m}^{i} = 13.6$ m/s, $2 f_{Dop}^{i} = 112$ H_z)		1.43×10^{-6}	7.15×10^{-8}
Aberration ($Z_{M}^{L} = 100$ m/s)		19.3×10^{-6}	9.65×10^{-8}
Ionospheric differential (.1° 1 way refraction)		2.35×10^{-3}	1.17×10^{-4}
Atmospheric differential (.3° 1 way refraction, 2% irregularity)		6.00×10^{-3}	3.00×10^{-4}
Pointing Error (Deg.)	Peak	8.35×10^{-3}	4.175×10^{-4}
	PSS	6.44×10^{-3}	3.221×10^{-4}
Pointing Loss (%)	Peak	1.19	.60
	RSS	.92	.46

Random Errors for 3 Layers Phase Distribution

Phase Errors (Deg)

Source	Deg.
Phase Jitter	1.13
Transmitter Noise (C/N = 30 db)	.36
Conjugators ($\delta_c = .6°$)	1.04
Lines ($\delta_{\ell} = 2.54°$)	6.22
Diplexers ($\delta_d = 1.81°$)	2.56
Transmitters ($\delta_p = 1.6°$)	1.60
Differential Doppler ($v_d = 6.25$ m/s)	.18
Peak:	13.09
RSS:	7.09

Phase Error Caused Loss: 1.53%

Table 7.1-2. Systematic and random amplitude and phase error goals for microwave power transmission system of space antenna. (Continued.)

SYSTEMATIC AMPLITUDE ERRORS (%)

Quantization	
16 level distribution	.078
8 level distribution	.312
Faraday rotation (worst year)	.48

Random Amplitude Errors (%)

Source	Peak	RMS
Transmit Power Fluctuation (1 db, rms)	10.64	1.18
Array Rotation ($L_s \leq 10$ m, $\Delta\theta_s = .15°$)	13.50	1.41
Peak:	24.14	RSS: 2.51

Amplitude Error Caused Loss:

For $\Delta\theta_s = .15°$	2.51%
$\Delta\theta_s = .05°$	1.34%

Summary of Losses

Source	Loss (%)
Random Phase	1.53
Random Amplitude ($\Delta\theta_s = .05°$)	1.34
Systematic Pointing (3 Pilot Station)	.46
Systematic Amplitude (8 Levels)	.32
Resultant Loss Associated With Spacecraft Array	3.65, RSS
Faraday Rotation (Houston, Worst Year)	.48%, "Average" Peak

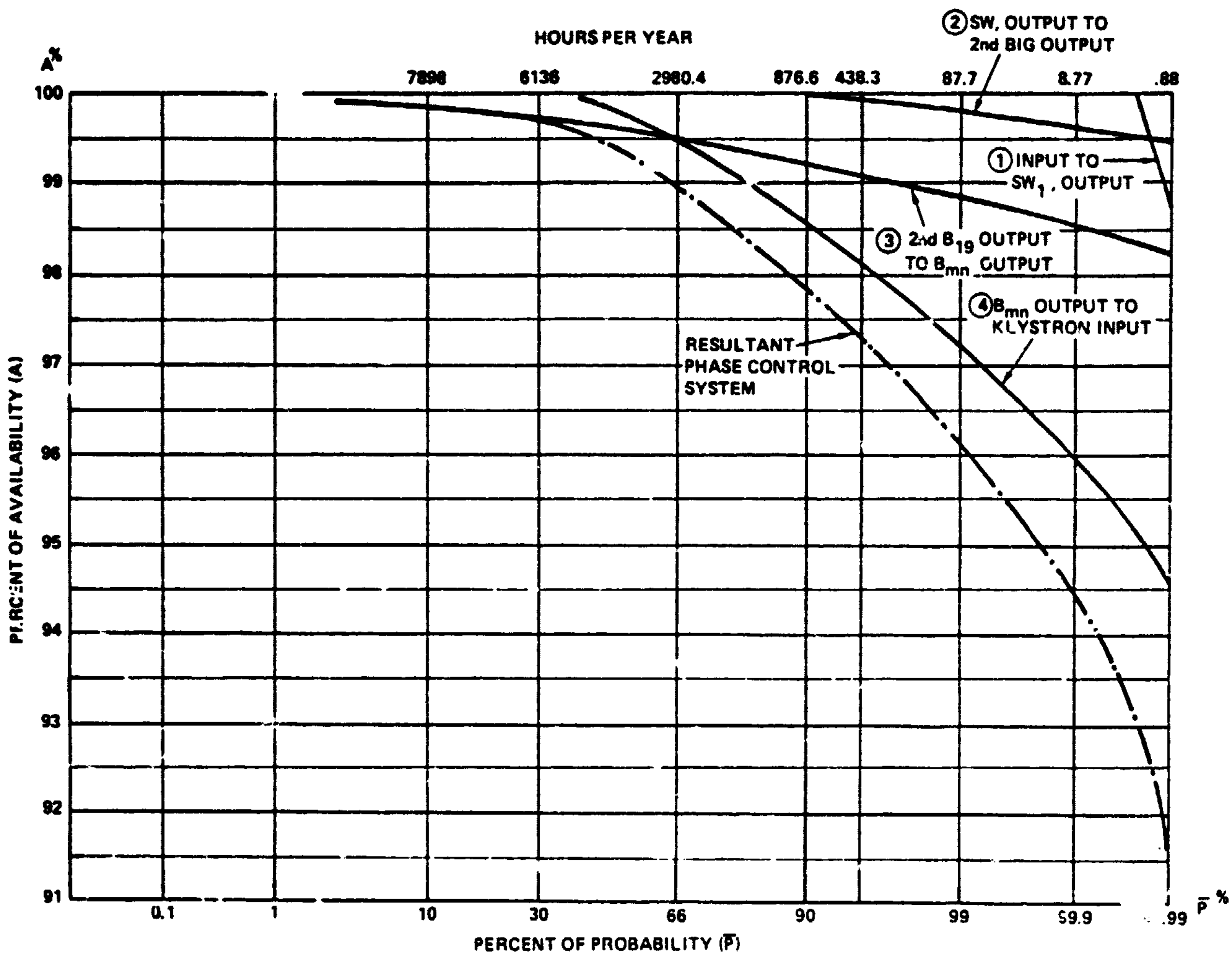

Figure 7.1-1. Availability versus probability goal for phase control system of space antenna from input of pilot signal receive antenna to input of klystron.

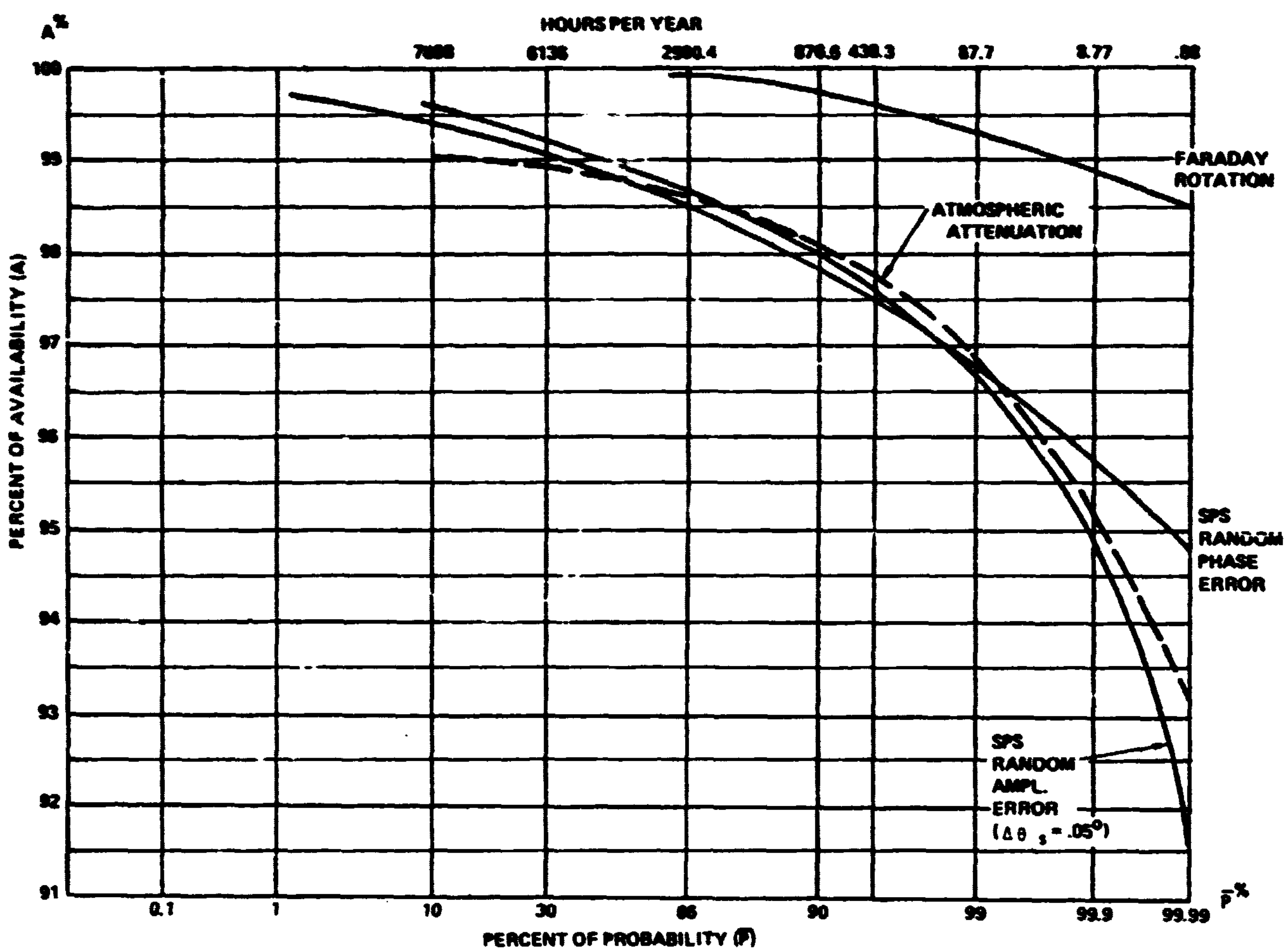

Figure 7.1-2. Availability versus probability goal for space antenna power output as affected by random aperture errors and propagation conditions.

C-4

SPS RESEARCH PLANNING DETAILED WORKSHEET

SUB PROGRAM	SUBJECT	KEY QUESTIONS	IMPLICATIONS	APPLIC ABILITY	TASK AND NETWORK NO.	DURATION (WORK DAYS)	NON-RESOURCE COST	TASKS FED AND LAGS	RESOURCES
Power transmission	Subarray	How many line source types are needed? How many power divider/combiner types are necessary? What electrical, mechanical, thermal characeristics are achievable? What are the material, fabrication, packaging, assembly problems? What tolerances are necessary and achievable? Is there a long term aging problem? What frequency band, power handling limitation exists? What industrial facilities are needed for production? What rates are achievable?	Achievable transmission efficiency, reliability, weight, production rate, cost. May need material development. Interface with structure, power amplifiers. Could influence practical bandwidth, frequency plan, ultimate No. of SPS's, lifetime. Could influence PA design.	All SPS's using planar array transmit antennas.	1. Continue system level studies 011103019	500	100K		2.1
					2. Design, fab and test all necessary types. 010304019	750	500K	011103029 010305019 SS100	1.1:2 4.1.1 1.3:0.5 4.2:2 3.2:0.5 2.1:0.5 2.1:0.5 10.5:0.5 3.4:1 3.5:2 1.4:2 3.1:1
					3. Test modules in space environment. 010304019	750	10M		

are given in normally-scheduled approx. 250 per calendar year.

costs are for materials and included in resources

(3) Lag notation: SS - start-to-start
FS - finish-to-start

(4) Resources are defined in resources library.
Values are headcount for each type.

(5) Task numbering code: AA BB CC DD E
AA designates program phase:
01 = ground-based research;
02 = research flight tests.
BB designates technical area, e.g., solar arrays
CC designates subject; e.g., silicon solar cells
DD designates task #
E designates priority, 0-9 with 9 highest.

SPS RESEARCH PLANNING DETAILED WORKSHEET

SUB PROGRAM	SUBJECT	KEY QUESTIONS	IMPLICATIONS	APPLIC ABILITY	TASK AND NETWORK NO.	DURATION (WORK DAYS)	NON RESOURCE COST	TASKS FED AND LAGS	RESOURCES
Power transmission	RF diplexer	How many types are needed? What isolation is practical? Separate or common receive aperture? What bandwidth is desirable? How it impacts weight, loss, isolation, stability, aging, temperature range? How many cavities? What types? Where should the diplexer be located? What material? Fabrication, alignment methods? Installation, verification methods?	Achievable transmission efficiency, reliability, production rate, weight, cost. May need material development. Impacts receiver design, ground pilot power. Interface with subarray.	All SPS's.	1. Continue system level studies. 011103019	500	50K		2.1
					1. Design fab and test a number of basic types. 010304019	500	200K	011103029	1.4

NOTES

(1) Durations are given in normally-scheduled work days, approx. 250 per calendar year.

(2) Non-resource costs are for materials and equipment not included in resources library.

(3) Lag notation: SS - start-to-start
FS - finish-to-start

(4) Resources are defined in resources library.
Values are headcount for each type.

(5) Task numbering code: AA BB CC DD E
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E designates priority, 0-9 with 9 highest.

SPS RESEARCH PLANNING DETAILED WORKSHEET

SUB PROGRAM	SUBJECT	KEY QUESTIONS	IMPLICATIONS	APPLIC ABILITY	TASK AND NETWORK NO.	DURATION (WORK DAYS)	NON-RESOURCE COST	TASKS FED AND LAGS	RESOURCES
Power transmission	IF diplexer	How many IF? What is optimum frequency plan? What is separation between tones? What frequency band? What is optimum loss, isolation, match? What is the effect of temperature? Where should be located?? What is diplexer contribution to phase distributing system errors? What is optimum implementation configuration?	Frequency plan, modulation technique, power levels, errors in phase distribution system.	All SPS's that use microwave power transmission.	1. Continue system level studies. 011103019	250	50K		
					2. Design, build and test diplexers. 010304019	500	200K		

NOTES

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Power transmission	Phase distribution cable.	What type? What is optimum loss-weight tradeoff point? Temperature effect? Aging? Differential expansion between center and outer conductor? Is redundancy needed? What failure modes exist? How to install? How to check? Is acceptable type available or needs new development?	Effects phase distribution tree layout, redundancy, reliability, levels in network, phase errors.	All SPS's that have microwave power transmission.	1. Continue system level studies.	250	20K		
					2. Implement simulation for applicable environmental conditions.	400	150K		

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Power transmission	Monitor control network.	Which are the key characteristics to monitor? How frequently? What accuracy? How much on-board processing? How much ground processing? What control strategy should be adapted? What is data volume? What telemetry system should be used? (Frequency, bandwidth, modulation, power.)	Determines required telemetry capacity. Influences availability, power transmission efficiency, maintenance requirements, maintenance procedures.	All SPS's.	System design.	500	500K		

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Power transmission	Phase computing phase control system	Is it feasible? How it compares to baseline? Is its speed adequate? Where is accuracy-speed-cost tradeofff optimum? What is band-width requirement? What is reliability? Impact on maintenance, cost, power, consumption, weight? What is optimum architecture? What new technologies are needed?	Cost, accuracy, develop-ment requirement, main-tenance, weight.	All SPS's.	1. Analyze and optimize phase computing system.	500	300K		
					2. Simulate operation by computer model.	200	100K		

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Power transmission	Pilot transmit station.	How many antenna locations? What is optimum antenna size-transmit power trade-off? How many transmitters? What phase and amplitude control? What modulation? Bandwidth? Control-monitor requirements? What is optimum location? Redundancy?	Selection may effect phase control system design. Affects achievable accuracy, risk, development cost.	All retro-directive SPS's.	1. Develop system design. 2. Develop specifications.	400	200K		

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7.1.2 Technology Development Tasks for Rectenna

Eight major technology development tasks have been identified in this area. These are listed in Table 7.1-3.

Table 7.1-3. Technology development tasks for Rectenna.

NO.	DESCRIPTION	CRITICAL	DESIRABLE	LEVEL OF INITIAL EFFORT (MAN MONTH)
1	RECTENNA ELEMENTS FOR 4 DIFFERENT EFFECTIVE RECEIVE AREA VALUES	X		60
2	CONTROL OF EDGE OF PANEL DIFFRACTION METHODS		X	12
3	LOAD HANDLING TECHNOLOGY, TRANSIENTS, THERMAL/VOLTAGE HANDLING	X		8
4	SHORT TERM POWER STORAGE TECHNOLOGY		X	6
5	MODELING AND CONTROLLING RERADIATION IN THE FREQUENCY SPECTRUM	X		12
6	CONTROL AND MONITOR TECHNOLOGY	X		6
7	WEATHER PROTECTION TECHNOLOGY	X		4
8	PANEL FABRICATION AND INSTALLATION TECHNOLOGY			18
				126

The purpose of these developments is to achieve the design goals for the various components as they are detailed in Part 4, Phase 1 final report (General Electric Space Division, April 1979.)

The key issues related to rectenna technology are:

- o Efficiency of the four different type (size) rectenna elements.
- o Overload and weather protection.
- o Achievement of availability.
- o Environmental effects during static and dynamic loading conditions.
- o Load handling.
- o Lifetime of rectenna panel.
- o Panel fabrication and installation technology.

The efficiency goals of the rectenna are listed in Table 7.1-4 as the minimum requirements. A particularly important efficiency factor is the microwave to DC conversion for which .72 must be considered as minimum acceptable and .80 as a desirable goal.

Table 7.1-4. Power transfer loss goals for microwave power tranmission system of SPS excluding equipment failures and propagation effects.

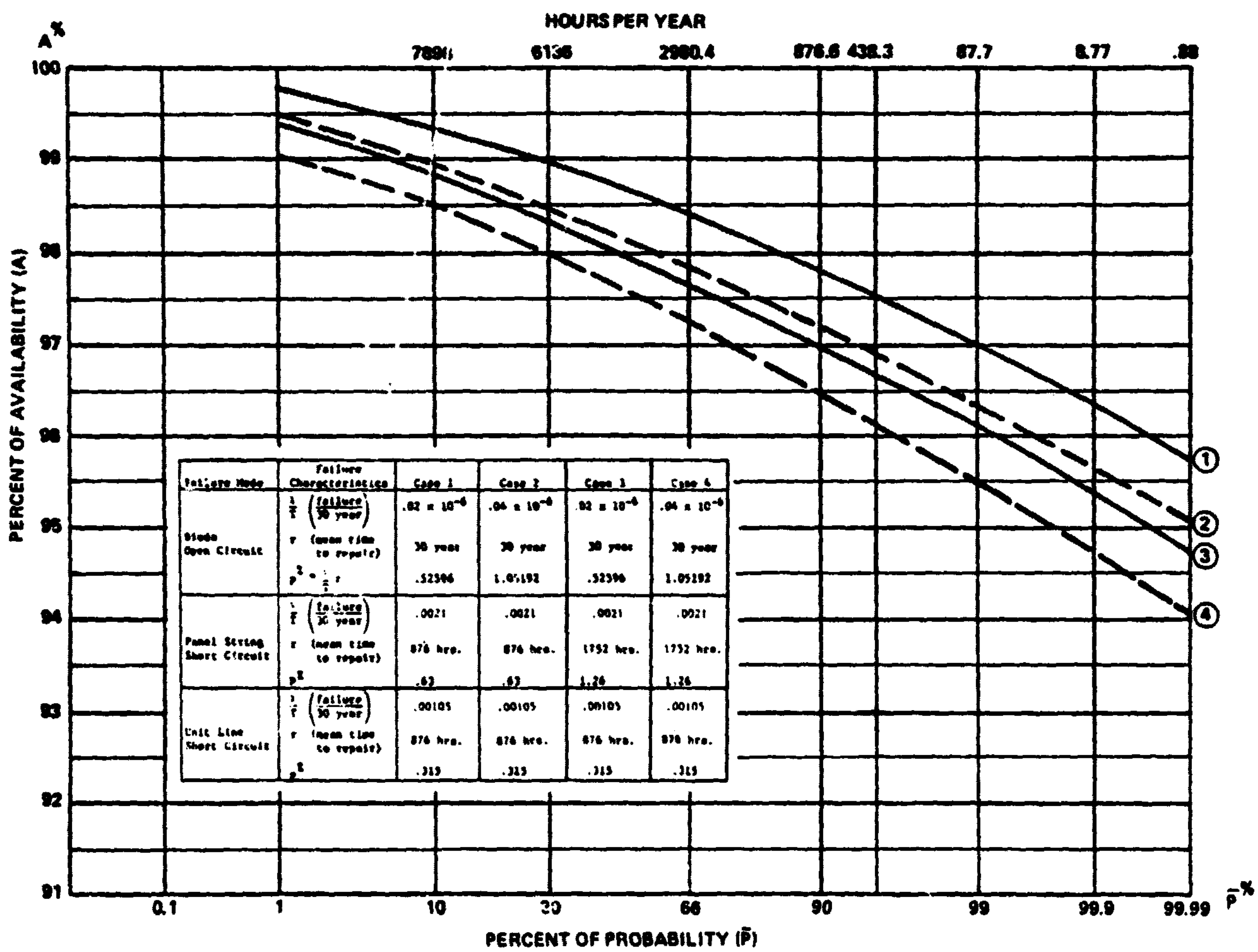
Input Interface: Output from transmit aperture of space antenna

Output Interface: Input to power grid

	Mw	Efficiency Factors		
Satellite RF Radiated Power	7124.9			
		.9534 (beam)		
Rectenna RF Input Power	6792.7			
		.7200 (resultant conversion)	.6769 (RF to DC)	.6667 (RF to AC)
Rectenna DC Input Power				
		.9861 (DC transmission)		
Rectenna DC Output Power	4823.3			
		.985 (AC conversion and transmission)		
Rectenna AC Output Power	4750.9			

Figures 7.1-3 and 7.1-4 displays the availability goals for the DC and AC part of the rectenna.

More definition of the technology development tasks are described in the attached "SPS reserach planning detailed work sheets."



Failure Mode	Failure Characteristics	Case 1	Case 2	Case 3	Case 4
Diode Open Circuit	λ (failure / 30 year)	$.02 \times 10^{-6}$	$.04 \times 10^{-6}$	$.02 \times 10^{-6}$	$.04 \times 10^{-6}$
	r (mean time to repair)	30 year	30 year	30 year	30 year
	$p^2 = \frac{\lambda}{2} r$	.52396	1.05192	.52396	1.05192
Panel String Short Circuit	λ (failure / 30 year)	.0021	.0021	.0021	.0021
	r (mean time to repair)	876 hrs.	876 hrs.	1752 hrs.	1752 hrs.
	p^2	.63	.63	1.26	1.26
Unit Line Short Circuit	λ (failure / 30 year)	.00105	.00105	.00105	.00105
	r (mean time to repair)	876 hrs.	876 hrs.	876 hrs.	876 hrs.
	p^2	.315	.315	.315	.315

Figure 7.1-3. Availability versus probability goal for rectenna D-C power collection system for various failure characteristics combinations.

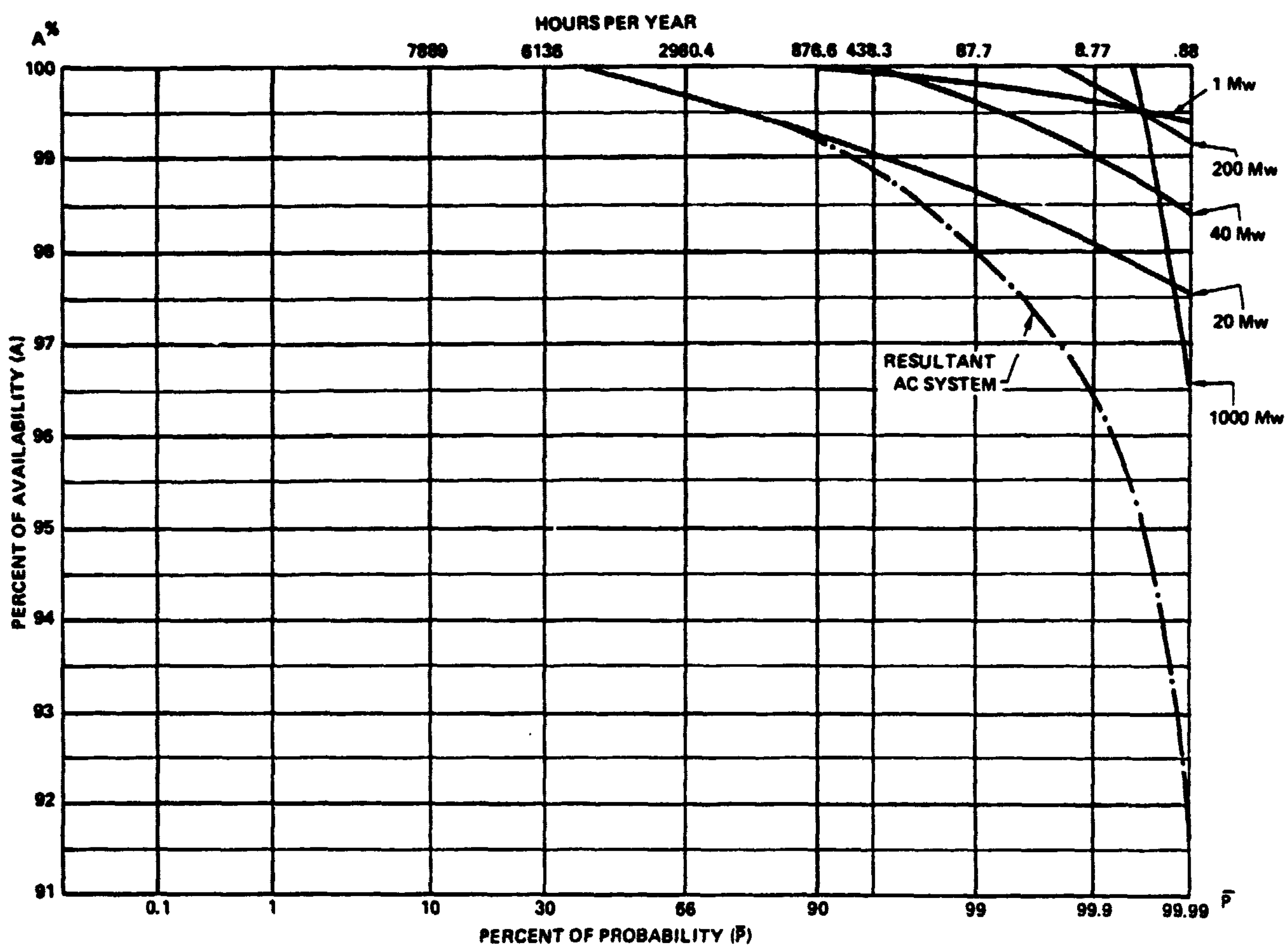


Table 7.1-7. Availability versus probability goals for rectenna A-C power collection system.

SPS RESEARCH PLANNING DETAILED WORKSHEET

SUB PROGRAM	SUBJECT	KEY QUESTIONS	IMPLICATIONS	APPLIC ABILITY	TASK AND NETWORK NO.	DURATION (WORK DAYS)	NON-RESOURCE COST	TASKS FED AND LAGS	RESOURCES
Power transmission	Rectenna elements	How many type of rectenna elements and how many type of rectifier elements should be used? If one type of rectifier is optimum is 4 different rectenna element adequate? What is optimum receive area size for each element? What is optimum physical configuration electrically, mechanically, cost and fabricability point of view? What is achievable RF to DC conversion efficiency for optimum designs as a function of power level, incoming angle, temperature range, weather effects and ageing? What is reliability of optimum element?	Rectenna size, complexity, cost, production schedule. is determined by element. Rectenna efficiency/cost ratio is affected in a major way and SPS produced energy per cost significantly by element design. Fabrication methods are influenced by element design in a major way. Sensitivity to weather will be affected. Rectenna generated r-f noise may be influenced by circuit attached to elements.	All SPS's employing microwave power transmission.	1. Conduct theoretical study which is addressing all the key questions.	200	150K	010310029 SS100 011103019	1.1:0.5 3.2.0.5 1.3:0.5 1.4:1 1.7:0.5
					2. Breadboard at least 4 different receive area rectenna element as they are needed for overall rectenna layout. Verify theoretical predictions on elements. 3. Construct typical rectenna panels of each of the 4 basic types. Utilize these modules to verify fabrication concepts. Conduct RF tests on each panel types to verify efficiency, reradiation, etc. characteristics.	500	500K	011103029	1.1:1 1.3:1 1.4:2 1.7:0.5 3.1:1 3.2:1 3.4:1 3.5:1 4.1:1 4.2:1 4.7:0.5

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Power transmission	Rectenna panel edge diffraction	How much diffraction around the edge of rectenna panels influences the operation of the rectenna? Has the panel size significant influence? What is the effect on efficiency, lifetime of diodes? Can edge effects controlled so that overall efficiency is improved?	Diffraction affects rectenna efficiency. Its control may effect panel design and fabrication methods.	All SPS's employing microwave power transmission	1. Develope theoretical radiation model and trade-off curves showing relationship between panel geometries and net efficiency.	100	60K	010310039 011103019	
					2. Utilize rectenna panels to verify edge diffraction effects on current distribution in rectifiers and achievable efficiency.	250	200K	011103029	

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Power transmission	Load handling of rectenna	What is dynamic behavior of rectenna during variations of input power or output load? What limits of power changes and rate of changes are expected, for what reasons? What is tolerable? What control actions are necessary? What protection circuits? What typical scenarios are expected to control input or output loads? What monitor and control elements must be implemented? Who is responsible for control? What will be the environmental impact of input and output power variations?	Operation of the SPS system and its utility interface is affected, operational strategies are determined. Cost of energy unit is affected through amount of lost power and cost of necessary control and safety devices. Radiation of SPS during periods of power control outside rectenna may have effect on environment, communication. Dynamic power variation may generate new forms of energy usage relative to forms we know today.	All SPS's employing microwave power transmission.	1. Develop theoretical modules for various load variation scenarios. 2. Implement computer simulation of dynamic behavior of the system covering radiation characteristics, current and voltage transient characteristics in rectenna and output power transient behavior. 3. Implement experimental model on which load variations, circuit protection methods can be studied.	100	60K	010310029 011103019	1.1:0.5 3.2:0.5 1.3:0.5 1.6:1

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Power transmission	Short term energy storage	Is short term energy storage desirable to reduce effects of input or output power load fluctuation? What is the desirable storage capacity? What is best design approach and cost How storage capacity should be integrated with rectenna, how can it be controlled?	Can reduce necessary control speeds of SPS, reduce environmental impact, increase safety, improve quality of service. May complicate rectenna design. Can improve lifetime of components.	All SPS's employing microwave power transmission.	1. Analyze requirements, design and use of short term energy storage system and determine its usefulness.	100	60K	010310029	

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Power transmission	Rectenna reradiation	What is the level of rectenna power reradiation as a function of angle, frequency, failure and polarization? In this level environmentally harmful? Can it be controlled by rectenna design, site selection, R-F fence around rectenna? If control is necessary and feasible what is the impact on rectenna efficiency, cost? What is reradiation behavior during transient and failure conditions? What is reradiation with rain, snow or ice load conditions?	Could effect environmental acceptability of SPS. Could effect site selection, control methods, may have significant cost impact.	All SPS's employing microwave power transmission.	1. Determine answers to key questions on the basis of theoretical models.	200	120K	019310029	
					2. Study rain and snow and ice conditions for efficiency and reradiation behavior of rectenna panel.	200	200K	011103079	

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Power transmission	Control monitor of rectenna.	What rectenna characteristics shall be monitored and controlled, how many points, how frequently? How the control-monitor system looks like, what is optimum implementation? What frequency band and bandwidth is necessary for data collection? How much data processing capacity is needed? How data will be used.	Affects rectenna design, operation, efficiency, reliability.	All SPS's employing microwave power transmission.	1. Develop control monitor system concept, basic characteristics and cost estimate.	150	80K	010310029	

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Power transmission	Weather protection of rectenna.	How weather is affecting rectenna design, lifetime, operation and cost? Will site selection have major impact? Is deicing necessary or practical for certain sites? Can SPS power be used for deicing? What is cost tradeoff for external power deicing methods? How efficiency varies as a function of weather? Is this a major contribution to average efficiency? Is "radome" type of protection of element necessary, desirable, practical, economical?	Weather protection of rectenna will influence receive element and panel design and cost. Cost of weather protection must be traded off against longer transmission lines. Weather effects may influence site selection.	All SPS's employing microwave power transmission.	1. Analyze weather effects and develop necessary protection schemes.	250	140K	010310029	

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Power transmission	Rectenna panel fabrication and installation	What is optimum configuration for the various type of receive elements? What is optimum material selection, how can production, test and installation be automated? Is any new material necessary? What new fabrication, installation test equipment has to be developed?	Fabrication technology has major impact on cost, schedule, material resources.	All SPS's employing microwave power transmission	1. Develop alternative fabrication concepts.	200	100K	0103100029	1.8 1.9
					2. Implement pilot fabrication on a reasonably scale to verify producibility and cost assumptions.	750	10M		1.8 1.9 3.1 3.4 3.5 4.1 4.2 4.3 4.4

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